

A Groundbased Imaging Study of Galaxies Causing DLA, subDLA, and LLS Absorption in Quasar Spectra^{*}

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ABSTRACT

We present results from a search for galaxies that give rise to damped Lyman alpha (DLA), subDLA, and Lyman limit system (LLS) absorption at redshifts $0.1 \lesssim z \lesssim 1$ in the spectra of background quasars. The sample was formed from a larger sample of strong Mg II absorbers ($W_0^{\lambda 2796} \geq 0.3 \text{ \AA}$) whose H I column densities were determined by measuring the Ly α line in HST UV spectra. Photometric redshifts, galaxy colours, and proximity to the quasar sightline, in decreasing order of importance, were used to identify galaxies responsible for the absorption. Our sample includes 80 absorption systems for which the absorbing galaxies have been identified, of which 54 are presented here for the first time. In some cases a reasonable identification for the absorbing galaxy could not be made.

The main results of this study are: (i) the surface density of galaxies falls off exponentially with increasing impact parameter, b , from the quasar sightline relative to a constant background of galaxies, with an e -folding length of ≈ 46 kpc. Galaxies with $b \gtrsim 100$ kpc calculated at the absorption redshift are statistically consistent with being unrelated to the absorption system, and are either background or foreground galaxies. (ii) $\log N_{\text{HI}}$ is inversely correlated with b at the 3.0σ level of significance. DLA galaxies are found systematically closer to the quasar sightline, by a factor of two, than are galaxies which give rise to subDLAs or LLSs. The median impact parameter is 17.4 kpc for the DLA galaxy sample, 33.3 kpc for the subDLA sample, and 36.4 kpc for the LLS sample. We also find that the decline in $\log N_{\text{HI}}$ with b can be roughly described by an exponential with an e -folding length of 12 kpc that occurs at $\log N_{\text{HI}} = 20.0$. (iii) Absorber galaxy luminosity relative to L^* , L/L^* , is not significantly correlated with $W_0^{\lambda 2796}$, $\log N_{\text{HI}}$, or b . (iv) DLA, subDLA, and LLS galaxies comprise a mix of spectral types, but are inferred to be predominantly late type galaxies based on their spectral energy distributions. (v) The properties of low-redshift DLAs and subDLAs are very different in comparison to the properties of gas-rich galaxies at the present epoch. A significantly higher fraction of low-redshift absorbers have large b values, and a significantly higher fraction of the large b value galaxies have luminosities $L < L^*$. The implications of these results are discussed.

Key words: quasars: absorption lines – galaxies: ISM – galaxies: statistics

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cooperative agreement with the National Aeronautics and Space Administration. The Hiltner 2.4 m Telescope on Kitt Peak is operated by MDM Observatory, which at the time was a joint facility of University of Michigan, Dartmouth College, Ohio State University, and Columbia University.

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1 INTRODUCTION

The recognition that damped Ly α absorption-line systems (DLAs) seen in quasar spectra arise in neutral-gas-rich foreground galaxies (Wolfe et al. 1986) motivated new methods for high-redshift galaxy studies ≈ 25 years ago. These high HI column density systems, with $N_{HI} \geq 2 \times 10^{20}$ atoms cm^{-2} , trace the bulk of the observed neutral gas in the Universe, and they are, therefore, powerful probes of galaxy formation and evolution back to the redshifts of the most distant quasars. Larger datasets and deeper surveys (e.g. Prochaska, Herbert-Fort, & Wolfe 2005; Rao, Turnshek, & Nestor 2006, henceforth, RTN06; Noterdaeme et al. 2009) have improved our knowledge of the neutral gas content and distribution at all observable redshifts, including the present epoch (Ryan-Weber et al. 2003; Zwaan et al. 2005). No other technique has revealed comparable reservoirs of neutral gas beyond the local Universe. See Rao (2005) and Wolfe et al. (2005) for some past reviews. Few DLAs were known at low redshift prior to the turn of the century because the Ly α line falls in the UV for $z < 1.65$. Thus, in the absence of large UV spectroscopic surveys, this meant that studies of neutral gas in what corresponds to the most recent $\approx 70\%$ of the age of the Universe¹ were problematic. But now MgII-based UV spectroscopic surveys (with HST-FOS, HST-STIS, HST-ACS Grism, and GALEX Grism) are identifying significant numbers of low-redshift DLAs and subDLAs (Rao & Turnshek 2000; RTN06; Monier et al. 2009a; Turnshek et al. in prep). The Mg II -based surveys for DLAs, which are designed to be unbiased (RTN2006), can be used to infer the incidence and cosmic neutral gas mass density at $z < 1.65$ (e.g. RTN06). Also, while subDLA absorbers, those with $10^{19} \leq N_{HI} < 2 \times 10^{20}$ atoms cm^{-2} , do not contribute much to the cosmic neutral gas mass density (Péroux et al. 2005), they are often found to have higher metallicities than DLAs (Kulkarni et al. 2007 and references therein). Lyman Limit System (LLS) absorbers are simply those with $N_{HI} \gtrsim 3 \times 10^{17}$ atoms cm^{-2} . Both subDLAs and LLSs generally exhibit Mg II absorption, and all strong Mg II systems, those with $W_0^{\lambda 2796} \geq 0.3$ Å, are Lyman limit systems (e.g., Churchill et al. 2000). However, unbiased Mg II -based surveys for subDLAs and LLS have never been implemented.

With the identification of DLAs (and subDLAs and LLSs), follow-up work involving the study of their host galaxies, environments, neutral-gas-phase metallicities, kinematics, 21 cm spin temperatures (when possible), ionization conditions, and numerical and semi-analytic modeling has kept many astronomers busy for decades.² Despite this, a consensus on certain aspects of DLAs is still lacking. Our previous studies indicated that DLA galaxies are

of mixed morphology and that the highest N_{HI} systems have the smallest impact parameters, but are hosted by low luminosity ($L < 0.2L^*$) galaxies (Rao et al. 2003; Turnshek et al. 2001; see also Chun et al. 2006). On the other hand, while Chen & Lanzetta (2003) and Chen, Kennicutt, & Rauch (2005) conclude that DLA galaxies span a mix of morphological types, they also propose that a large contribution from dwarf galaxies is not required to explain the properties of DLAs. In addition, Zwaan et al. (2005) suggest that the local galaxy population can completely explain the properties of known low-redshift DLA galaxies. Studies of Mg II galaxies, of which DLAs form a subset, have also revealed a mix of morphological types (e.g. Churchill, Kacprzak, and Steidel 2005; Kacprzak et al. 2007), although most appear to be spirals and the majority exhibit minor perturbations (as seen in HST images). From stacked images of over 2800 SDSS quasar sightlines containing MgII absorption, Zibetti et al. (2007) derive an Sbc-type average colour and $0.5L^*$ average luminosity for the absorbing galaxies. Images of quasar sightlines with “ultra-strong” Mg II systems³ point to outflows from bright ($L > L^*$) starbursting galaxies as the cause of the kinematically-complex absorption (Nestor et al. 2007; 2010). A large fraction of these are known to be DLAs (RTN06). However, the ultra-strong Mg II regime is not addressed in this paper.

Semi-analytic and numerical models, some of which are based on results from high-resolution spectroscopic data of DLA metal absorption lines, have resulted in a variety of often competing scenarios for DLAs: large rapidly rotating protogalactic disks (Prochaska & Wolfe 1997, 1998; Wolfe & Prochaska 1998), merging protogalactic clumps in a hierarchical merging scenario (Haehnelt et al. 1998), low surface brightness galaxies (Jimenez et al. 1999), dwarf galaxies (Okoshi & Nagashima 2005), compact, faint galaxies with impact parameters smaller than 5 kpc at $z \sim 3$ (Nagamine et al. 2007), and the outer regions of high- z Lyman break galaxies (Møller et al. 2002; Wolfe et al. 2003). Recent high-quality H I 21 cm data of local galaxies indicate that DLA gas velocity widths are more consistent with tidal gas related to galaxy interactions or superwinds rather than galaxy disks (Zwaan et al. 2008). In addition, some recent compelling cosmological simulations relevant to interpreting the nature of Mg II -selected galaxies in general, and DLA galaxies in particular, have been presented by Kacprzak et al. (2010).

However, there is a dearth of identified DLA (and subDLA) galaxies, and this has undoubtedly motivated the various interpretive scenarios. Therefore, larger samples of neutral-gas-selected galaxies are required to investigate the possibilities, which in turn will help constrain models of galaxy evolution and better establish the galaxy population that harbors the bulk of the neutral gas in the Universe. Traditional galaxy surveys trace galaxies by virtue of their luminous emission. Beyond the local Universe far less is known about neutral-gas-selected galaxies and their relationship to luminosity-selected galaxies.

As an extension of our earlier work (Rao et al. 2003), we have undertaken a large multi-colour optical/IR imaging programme of quasar fields containing Mg II absorbers

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¹ The “737” cosmology is used throughout: $(\Omega_\Lambda, \Omega_m, h) = (0.7, 0.3, 0.7)$

² A recent search of the SAO/NASA Astrophysics Data System database identifies > 2000 papers.

³ Those systems with Mg II rest equivalent width $W_0^{\lambda 2796} \geq 3$ Å.

with measured N_{HI} . The absorbers were selected from Table 1 of RTN06, and were required to have absorption redshifts $z_{abs} \lesssim 1$ to optimize the possibilities for detection and characterization of galaxies in these fields. Data and results from eight DLAs in six quasar fields were presented in Turnshek et al. (2001), Rao et al. (2003), and Turnshek et al. (2004). Other observations from the literature were also considered. In total, 27 DLA, 30 subDLA, and 23 LLS galaxies (i.e. 80 absorbers in total) have been identified. In this paper, we present and analyse the entire dataset. These observations are described in §2. The identification of galaxies is described in §3 through specific examples. The entire dataset can be accessed on line at <http://enki.phyast.pitt.edu/Imaging.php>. A summary of the data and statistical inferences are presented in §4. Conclusions and discussion are presented in §5 and 6, respectively. Among other findings this work demonstrates that the neutral hydrogen column density, N_{HI} , is strongly correlated with impact parameter, b , in the sense that DLA galaxies are systematically closer to the quasar sightline, by a factor of two, than are galaxies which give rise to subDLAs and LLSs. We also find that the properties of low-redshift ($0.1 \lesssim z \lesssim 1$) DLAs and subDLAs are very different in comparison to the properties of H I -rich galaxies at the present epoch. A significantly higher fraction of low-redshift absorbers have large b , and a significantly higher fraction of the large b galaxies have luminosities $L < L^*$.

All magnitudes reported in this paper are in the AB system, and all distance related quantities are calculated using the “737” cosmology with $(\Omega_\Lambda, \Omega_m, h) = (0.7, 0.3, 0.7)$.

2 OBSERVATIONS

The imaging data were obtained between December 1998 and June 2005 through community-access time at national facilities as well as through Ohio State University’s share of time at the MDM Observatory. The various telescopes and detectors that were employed, as well as the varying observing conditions that prevailed over the better part of a decade of observations, resulted in an unavoidably inhomogeneous dataset. Nevertheless, since most of the data are well calibrated and reach fainter magnitudes than large groundbased surveys such as the Sloan Digital Sky Survey, this observing programme has yielded the most useful and comprehensive set of images of DLA, subDLA, and LLS absorption-line-producing galaxies that has thus far been obtained.

The optical images were obtained at Kitt Peak National Observatory in Arizona. The telescopes and corresponding detectors used were 1) the KPNO 2.1 m with the T2KA or T2KB CCDs covering a $10.4' \times 10.4'$ field-of-view at a scale of $0.305''/\text{pixel}$, 2) the MDM Observatory 2.4 m Hiltner with the 1024×1024 Templeton CCD covering a $4.72' \times 4.72'$ field-of-view at $0.275''/\text{pixel}$, and 3) the 3.5 m WIYN with the Tip-Tilt Module (WTTM) covering a $3.84' \times 4.69'$ field-of-view at $0.1125''/\text{pixel}$. The near-infrared images were obtained on Mauna Kea, Hawaii, with the NASA IRTF 3.0 m telescope using NSFCAM which has a $76.8'' \times 76.8''$ field-of-view at $0.30''/\text{pixel}$. The detector was the 256×256 InSb array. A few images were obtained with the SpeX infrared slit-viewer/guider covering a $60'' \times 60''$ field-of-view at $0.12''/\text{pixel}$ with the Raytheon 512 \times 512 InSb

array. The optical images taken with the KPNO 2.1 m or WIYN telescopes were obtained using the Johnson-Cousins U, B, R, I or u', g', r', i' KPNO SLOAN filters, and those observed at MDM were observed with the MDM Gunn-Thuan u, g, r, i filters. Henceforth, we ignore the differences between the SDSS and Gunn-Thuan filter sets since the transformation between them is small. Near-infrared images were taken using the standard Mauna Kea Observatory J, H, K filter set.

Optical data were taken in groups of 3 or 4 offset exposures ranging from 900 to 1800 seconds per exposure, and standard data reduction procedures were followed. The infrared observations were carried out using a series of either 30 or 60 dithered short exposures ranging from 2 to 20 seconds per exposures. The individual exposure times were chosen to prevent the quasar point spread function from saturating. Flat fielding was done using sky frames constructed from the dithered object frames. Landolt standards were used to calibrate the Johnson-Cousins observations (Landolt 1992). Photometric calibration of fields that overlapped with SDSS images was performed by comparing our instrumental magnitudes with the SDSS DR4 photometry of point sources. The photometric zeropoint solution with corresponding errors for each frame were determined by a least squares fit to the SDSS magnitudes and our instrumental magnitudes. Generally, 10 or more isolated, unsaturated stars that were common to our images and the SDSS fields were used in the calibration. UKIRT faint photometric standards (Hawarden et al. 2001) were used to calibrate the near-infrared observations.

Table 1 lists the fields for which we obtained imaging data. The first six columns give details about the absorption-line system from RTN06. Column 1 gives the quasar name, column 2, the quasar magnitude, column 3, the quasar emission redshift, column 4 gives the redshift of the Mg II absorption-line system, column 5 the rest equivalent width of the stronger member ($\lambda 2796$) of the Mg II doublet, and column 6 gives the H I column density as measured from the *HST* UV spectrum. Column 7 lists the optical and infrared filters through which images of each quasar field were obtained. Here we summarize a few salient features of the dataset.

We were able to obtain a complete optical and infrared (*UBRIJHK* or *ugriJHK*) dataset for 18 of the 60 fields. The largest number of fields, 53, were observed in K , while the fewest, 26, were observed in U (or u). Figure 1 gives the distribution of 3σ surface brightness limits reached in each filter. The infrared data show the least spread since almost all were obtained with the IRTF NSFCAM, with the exception of two observations with the (low-sensitivity) IRTF SpeX guide camera.

Since the K -band data are the most extensive as well as uniform, we illustrate a few properties of the dataset using the K -band data sample. Figure 2 is a plot of the K -band galaxy luminosity limit (in terms of L_K^* , where $M_K^* = -22.86$ for $z < 1$, Cirasuolo et al. 2006) as a function of redshift. Here, the 3σ limiting K -band surface brightness was used to estimate the luminosity of a fiducial 10 kpc-sized galaxy that can be detected at the redshift of the absorber. K -corrections appropriate for an Sb type galaxy have been applied to all datapoints.

The distribution of seeing values for our data, expressed

Table 1. The Imaging Sample

Quasar	Mag. ^a	z_{em}	MgII z_{abs}	MgII $W_0^{\lambda 2796}$ (Å)	$\log N_{\text{HI}}(\text{cm}^{-2})$	Filters
0021+0043	17.7	1.245	0.5203	0.533±0.036	19.54 ^{+0.02} _{-0.03}	JHK
...	...	...	0.9420	1.777±0.035	19.38 ^{+0.10} _{-0.15}	...
0041-266	17.8	3.053	0.8626	0.67±0.06	<18.00	R
0058+019	17.2	1.959	0.6127	1.666±0.003 ^b	20.04 ^{+0.10} _{-0.09}	UIK
0107-0019	18.3	0.738	0.5260	0.784±0.080	18.48 ^{+0.30} _{-0.63}	JHK
0116-0043	18.7	1.282	0.9127	1.379±0.096	19.95 ^{+0.05} _{-0.11}	JHK
0117+213	16.1	1.491	0.5764	0.91±0.04	19.15 ^{+0.06} _{-0.07}	UBRIJHK
0123-0058	18.6	1.551	0.8686	0.757±0.098	<18.62	JHK
0138-0005	18.7	1.340	0.7821	1.208±0.096	19.81 ^{+0.06} _{-0.11}	JHK
0139-0023	19.0	1.384	0.6828	1.243±0.102	20.60 ^{+0.05} _{-0.12}	JHK
0141+339	17.6	1.450	0.4709	0.78±0.07	18.88 ^{+0.08} _{-0.10}	g'r'i'JK
0152+0023	17.7	0.589	0.4818	1.340±0.057	19.78 ^{+0.07} _{-0.08}	H
0153+0009	17.8	0.837	0.7714	2.960±0.051	19.70 ^{+0.08} _{-0.10}	JHK
0253+0107	18.8	1.035	0.6317	2.571±0.166	20.78 ^{+0.12} _{-0.08}	g'r'i'JHK
0254-334	16.0	1.849	0.2125	2.23	19.41 ^{+0.09} _{-0.14}	BRIJK
0256+0110	18.8	1.349	0.7254	3.104±0.115	20.70 ^{+0.11} _{-0.22}	g'HK
0420-014	17.0	0.915	0.6331	0.75±0.02 ^b	18.54 ^{+0.07} _{-0.10}	BRIJHK
0454+039	16.5	1.343	0.8596	1.45±0.01	20.67 ^{+0.03} _{-0.03}	JHK
0710+119	16.6	0.768	0.4629	0.62±0.06	<18.30	g'r'
0735+178	14.9	...	0.4240	1.32±0.03	<19.00	UBRIJHK
0843+136	17.8	1.877	0.6064	0.938±0.035 ^c	19.56 ^{+0.11} _{-0.14}	u'g'r'i'JHK
0953-0038	18.4	1.383	0.6381	1.668±0.080	19.90 ^{+0.07} _{-0.09}	urJHK
0957+003	17.6	0.907	0.6720	1.936±0.118 ^c	19.59 ^{+0.03} _{-0.03}	UBRIJHK
1009-0026	17.4	1.244	0.8426	0.713±0.038	20.20 ^{+0.05} _{-0.06}	JHK
...	...	...	0.8866	1.900±0.039	19.48 ^{+0.01} _{-0.08}	...
1009+0036	19.0	1.699	0.9714	1.093±0.111	20.00 ^{+0.11} _{-0.05}	JHK
1019+309	17.5	1.319	0.3461	0.70±0.05	18.18 ^{+0.08} _{-0.10}	K
1028-0100	18.2	1.531	0.6322	1.579±0.087	19.95 ^{+0.05} _{-0.08}	JHK
...	...	...	0.7087	1.210±0.066	20.04 ^{+0.07} _{-0.04}	...
1047-0047	18.4	0.740	0.5727	1.063±0.117	19.36 ^{+0.17} _{-0.19}	JHK
1048+0032	18.6	1.649	0.7203	1.878±0.063	18.78 ^{+0.18} _{-0.48}	u'g'r'i'JHK
1107+0048	17.5	1.392	0.7404	2.952±0.025	21.00 ^{+0.02} _{-0.05}	ugriJHK
1109+0051	18.7	0.957	0.4181	1.361±0.105	19.08 ^{+0.22} _{-0.38}	g'r'i'JHK
...	...	...	0.5520	1.417±0.085	19.60 ^{+0.10} _{-0.12}	...
1209+107	17.8	2.193	0.3930	1.00±0.07	19.46 ^{+0.08} _{-0.18}	u'g'r'i'JHK
...	...	...	0.6295	2.619±0.083 ^c	20.30 ^{+0.08} _{-0.30}	...
1225+0035	18.9	1.226	0.7730	1.744±0.138	21.38 ^{+0.11} _{-0.12}	JHK
1226+105	18.5	2.305	0.9376	1.646±0.110 ^c	19.41 ^{+0.12} _{-0.18}	UBRJHK
1323-0021	18.2	1.390	0.7160	2.229±0.071	20.54 ^{+0.15} _{-0.15}	ugriJHK
1342-0035	18.2	0.787	0.5380	2.256±0.068	19.78 ^{+0.12} _{-0.14}	ugriJHK
1345-0023	17.6	1.095	0.6057	1.177±0.049	18.85 ^{+0.15} _{-0.24}	u'g'r'i'JHK
1354+258	18.0	2.006	0.8585	1.176±0.076 ^c	18.57 ^{+0.07} _{-0.08}	BRIJK
...	...	...	0.8856	0.489±0.069 ^c	18.76 ^{+0.10} _{-0.13}	...
1419-0036	18.3	0.969	0.6238	0.597±0.069	19.04 ^{+0.07} _{-0.14}	HK
...	...	...	0.8206	1.145±0.057	18.78 ^{+0.26} _{-0.23}	...
1426+0051	18.8	1.333	0.7352	0.857±0.080	18.85 ^{+0.03} _{-0.03}	u'g'r'i'JHK
...	...	...	0.8424	2.618±0.125	19.65 ^{+0.09} _{-0.07}	...
1431-0050	18.1	1.190	0.6085	1.886±0.076	19.18 ^{+0.30} _{-0.27}	ugriJHK
...	...	...	0.6868	0.613±0.066	18.40 ^{+0.06} _{-0.08}	...
1436-0051	18.5	1.275	0.7377	1.142±0.084	20.08 ^{+0.10} _{-0.12}	u'g'r'i'JHK
...	...	...	0.9281	1.174±0.065	<18.82	...
1437+624	19.0	1.090	0.8723	0.71±0.09	<18.00	K
1521-0009	19.0	1.318	0.9590	1.848±0.096	19.40 ^{+0.08} _{-0.14}	u'r'g'i'J
1525+0026	17.0	0.801	0.5674	1.852±0.035	19.78 ^{+0.07} _{-0.08}	BRIJHK
1622+239	17.5	0.927	0.6561	1.471±0.050 ^c	20.36 ^{+0.07} _{-0.08}	K
...	...	...	0.8913	1.622±0.042 ^c	19.23 ^{+0.02} _{-0.03}	...

Table 1. Continued

Quasar	Mag. ^a	z_{em}	MgII z_{abs}	MgII $W_0^{\lambda 2796}$ (Å)	$\log N_{\text{HI}}(\text{cm}^{-2})$	Filters
1704+608	15.3	0.371	0.2220	0.562 ± 0.013^b	$18.23^{+0.05}_{-0.05}$	IJK
1714+5757	18.6	1.252	0.7481	1.099 ± 0.084	$19.23^{+0.17}_{-0.33}$	ugriJHK
1715+5747	18.3	0.697	0.5579	1.001 ± 0.067	$19.18^{+0.15}_{-0.18}$	u'g'r'i'JHK
1716+5654	19.0	0.937	0.5301	1.822 ± 0.130	$19.98^{+0.20}_{-0.28}$	ugri'JH
1722+5442	18.8	1.215	0.6338	1.535 ± 0.098	$19.00^{+0.30}_{-0.22}$	u'g'r'i'
1727+5302	18.3	1.444	0.9448	2.832 ± 0.070	$21.16^{+0.04}_{-0.05}$	u'g'r'i'JHK
...	...	...	1.0312	0.922 ± 0.057	$21.41^{+0.03}_{-0.03}$	...
1729+5758	17.5	1.342	0.5541	1.836 ± 0.046	$18.60^{+0.18}_{-0.43}$	u'g'r'i'JHK
1733+5533	18.0	1.072	0.9981	2.173 ± 0.069	$20.70^{+0.04}_{-0.03}$	u'g'r'i'HK
1857+566	17.3	1.578	0.7151	0.65	$18.56^{+0.05}_{-0.06}$	UBRIJHK
2149+212	19.0	1.538	0.9114	0.72	$20.70^{+0.08}_{-0.10}$	UBRIJK
...	...	...	1.0023	2.46	$19.30^{+0.02}_{-0.05}$	...
2212-299	17.4	2.706	0.6329	1.15 ± 0.02^b	$19.75^{+0.03}_{-0.03}$	BRJK
2223-052	18.4	1.404	0.8472	0.586 ± 0.012^b	$18.48^{+0.41}_{-0.88}$	BI
2328+0022	17.9	1.308	0.6519	1.896 ± 0.077	$20.32^{+0.06}_{-0.07}$	g'r'i'JHK
2334+0052	18.2	1.040	0.4713	1.226 ± 0.107	$20.65^{+0.12}_{-0.18}$	g'r'i'JHK
2353-0028	17.9	0.765	0.6044	1.601 ± 0.082	$21.54^{+0.15}_{-0.15}$	JHK

^aHere we provide m_V for quasars that pre-date SDSS (these can be identified by their 3-digit, 1950, Dec designation), and $(m_g + m_r)/2$ (approximately m_V) for SDSS quasars, which can be identified by their 4-digit, 2000, Dec designation. For consistency with our earlier work as well as for historical reasons, 1950 quasar names have not been altered to reflect 2000 co-ordinates.

^bMeasurements of $W_0^{\lambda 2796}$ have been changed from RTN06 values to reflect the more recent measurements of Mathes et al. (in preparation).

^cMeasurements of $W_0^{\lambda 2796}$ have been changed from RTN06 values to reflect the more recent measurements of Quider et al. (2011).

in terms of the FWHM of a point source, is shown in Figure 3. The seeing is a particularly important parameter for this study because the quasar point spread function (PSF) limits our ability to study the smallest impact parameters. For ground-based imaging, techniques such as adaptive optics (AO) achieve seeing values down to a few tenths of an arcsecond. However, the presence of a bright (12^{th} to 15^{th} magnitude), nearby (within $30''$), point source is generally required for implementing AO techniques. Since the (faint) quasar is the brightest object in the majority of our fields, we could not take advantage of AO. From Figure 3 it can be seen that the optical dataset has seeing values generally $\gtrsim 1''$, while for the infrared data, seeing values $\lesssim 1''$ were often achieved. We were able to probe smaller impact parameters than the seeing radius for images where the quasar PSF could be subtracted. However, this was not possible for all fields, because suitable PSF stars were not always available within the image, and we did not observe PSF stars separately. In Figure 4 we plot minimum detection impact parameter histograms for the K -band images in arcsec as well as in kpc at the redshift of the absorbers. The minimum detection impact parameter for fields where the quasar PSF could not be subtracted is conservatively taken to be the radius at which the PSF blended with the background. This estimate depends on the brightness of the quasar as well as on the seeing. For PSF-subtracted fields, the minimum detection impact parameter is measured as the radius of the mask that was applied to the subtraction residuals. The average minimum impact parameters for all fields is 7.3 ± 2.7 kpc. The average minimum impact parameter for PSF-subtracted fields is 5.2 ± 2.3 kpc, and for non-PSF subtracted fields, it is 9.1 ± 3.0 kpc. We note here that whether the quasar

PSF was, or was not, subtracted in our ground-based data has not influenced the identification of absorber galaxies (§3 and §4). For our K -band sample, we find that the distribution of impact parameters of absorber galaxies identified in our PSF-subtracted fields and non-PSF-subtracted fields are similar, with Kolmogorov-Smirnov (KS) test probability $P_{\text{KS}} = 0.93$.

The identification of galaxies causing absorption in quasar spectra is, undoubtedly, best achieved from space. Not being able to probe to within 5 or 10 kpc of the quasar sightline is the most severe limitation of a groundbased imaging programme. Low luminosity dwarf galaxies directly along the quasar sightline will most likely be missed, resulting in an incorrect identification of the absorbing galaxy. Below, we attempt to quantify the possible number of missed galaxies in our sample due to this bias.

3 IDENTIFICATION OF ABSORBING GALAXY CANDIDATES

The detection and photometry of sources were carried out using the automated software SExtractor (Bertin & Arnouts 1996). The SExtractor input parameter that defines the detection threshold for source identification was set to 1σ above the sky background, and the minimum detection area was set to 5 adjoining pixels. “Adjoining” as implemented in SExtractor refers to any pixels touching at corners or sides. A source is considered to be a confident detection if it was detected at the 2σ or higher level through more than one filter. Its position was determined using the image with the best seeing.

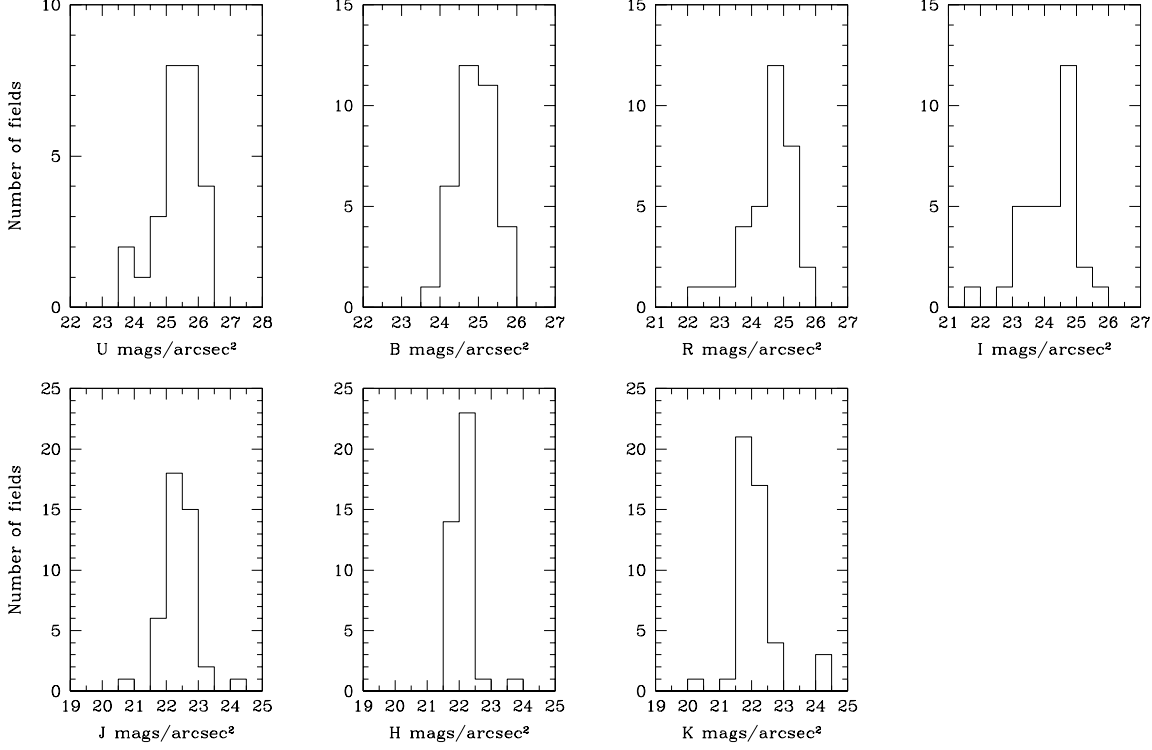


Figure 1. Distribution of 3σ surface brightness limits reached in the final reduced images for each of the seven filters.

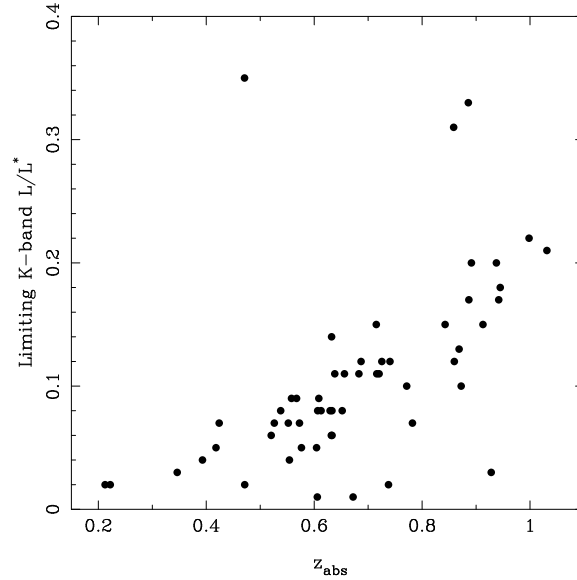


Figure 2. K -band luminosity of a fiducial 10-kpc sized galaxy that would be detectable at the redshift of the absorber as a function of redshift for our dataset. The luminosity is expressed in terms of L_K^* and is estimated from the 3σ limiting surface brightness achieved for each field. K -corrections appropriate for an Sb type galaxy have been applied.

Figure 1 shows that most of the K -band data (38 fields) reach surface brightnesses between 21.5 and 22.5 K magnitudes per square arcsec at the 3σ level. Figure 5 gives the redshift distribution of the 38 absorbers in these fields, 24 of which have redshifts $0.5 < z < 0.8$. This is a small enough redshift interval that we use a single value for the angular diameter distance to estimate the surface density of galaxies. We then use this sample to estimate: (1) the background

(and foreground) number density of galaxies, (2) the excess around the quasar line of sight that can be attributed to the presence of an absorbing galaxy or galaxies associated with it, and (3) the number of absorbing galaxies that might have been missed due to the glare of the quasar PSF. Figure 6 shows the number of galaxies per square kpc as a function of impact parameter from the quasar calculated in annuli of width 10 kpc. The red line is the best-fit exponential profile

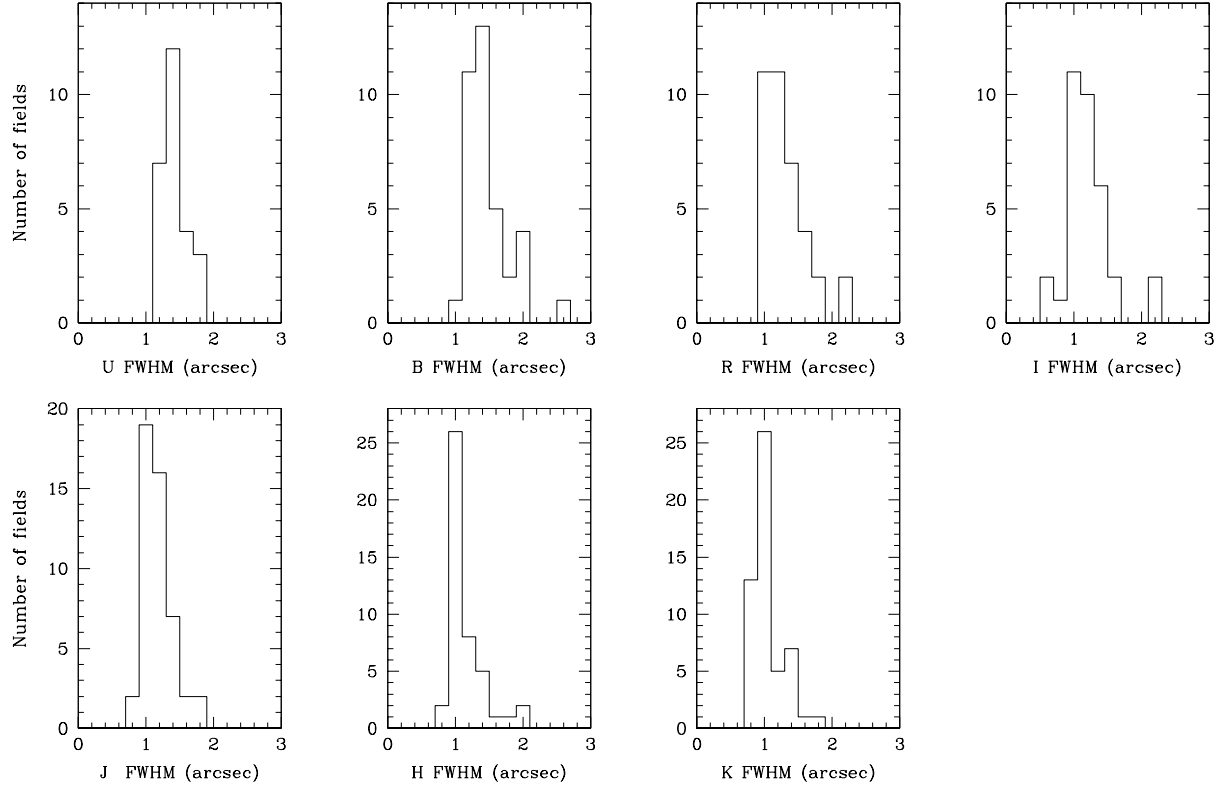


Figure 3. Distribution of seeing values obtained for observations in each filter. FWHM of point sources in the final reduced images are reported.

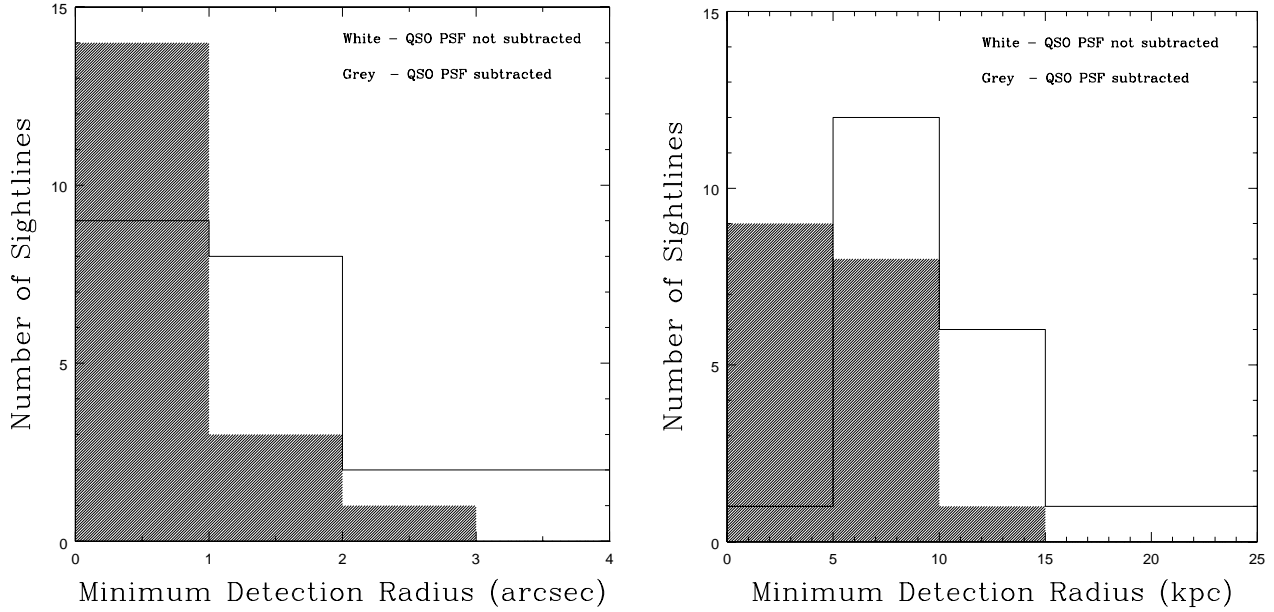


Figure 4. Distribution of minimum impact parameters from the quasar sightline for detection of galaxies in arcsec (left) and in kpc (right) at the redshift of the absorber. Fields for which the quasar PSF was subtracted are represented by the grey histogram. Not all fields had point sources (other than the quasar) that could be used to model the PSF, therefore, the quasar PSF was not subtracted in these fields. The minimum impact parameter for galaxy detection is, therefore, generally larger. This sample is represented by the unshaded histogram.

to the data with an e -folding length of 46.1 kpc. The horizontal asymptote, which occurs at $7.9 \times 10^{-5} \text{ kpc}^{-2}$, is shown by the blue dotted line. It represents the background plus foreground galaxy number density. Galaxies beyond $b \approx 100$ kpc can be considered background or foreground galaxies that are not associated with the absorption systems. Moreover, assuming that the distribution can be extrapolated to impact parameter $b = 0$ gives an estimate of the number of galaxies unaccounted for due to the presence of the quasar PSF and the inability to subtract it perfectly. This suggests that the expected number density at $b < 10$ kpc is $\approx 3.1(10^{-4})$ galaxies per square kpc per quasar field, and that ≈ 0.07 galaxy candidates per field might have been missed. Or, on average, one in every 14 fields may have a galaxy at $b < 10$ kpc that is not identified in our groundbased imaging survey. This amounts to approximately four among the 55 identified candidate galaxies in our survey (§4).

Based on the above analysis, only objects within an impact parameter $b = 100$ kpc from the quasar at the absorber redshift (or lowest absorber redshift in the case of multiple absorbers per quasar sightline) are catalogued for each field, since galaxies farther away can statistically be considered background or foreground galaxies.

The absorbing galaxy has not been confirmed spectroscopically for any of the fields presented here. A spectroscopic redshift that matches the absorption redshift would, of course, lead to a more confident identification of the absorbing galaxy (or a parcel of gas associated with it). In the absence of spectroscopic data, we assign a galaxy as a “candidate absorber” with varying levels of confidence based on several criteria. The highest level of confidence is achieved when a galaxy’s photometric redshift matches that of the Mg II absorption-line system within the uncertainties. Photometric redshifts were determined for galaxies that were detected in four or more filters.⁴ If more than one galaxy in the field was determined to have a photometric redshift that matched the absorption redshift, then the one closest to the quasar sightline was selected as the candidate absorber. Next, if photometric redshifts could not be determined (e.g., if a galaxy is detected in fewer than four filters), then we judged whether or not the galaxy’s colours were consistent with it being at the absorption redshift. This was done by comparing our measured galaxy colours with the colours derived from the redshifted ‘hyperz’ galaxy templates of Hewett et al. (2006), after converting our AB magnitudes to Vega magnitudes. Lastly, if no colour information was available, or if a galaxy’s colours were inconclusive, then the “proximity criterion” was used, whereby the galaxy closest to the quasar sightline was selected as the candidate absorber. For sightlines with two absorbers, assignment of the absorbing galaxies was often ambiguous. Depending on the specifics of the field, we were sometimes unable to assign a galaxy to the absorber. In addition, some fields were observed under non-photometric conditions, while for others no calibration information was available. Although photometry could not be carried out for the objects in these fields, impact parameter information could nevertheless be

extracted. The proximity criterion was employed in these cases as well. These galaxies are not part of the statistical sample analyzed here since no luminosity information exists for them.

We assign a “CL” value, or confidence level, for each galaxy identification. Galaxies which have been confidently identified through photometric redshifts that match the absorption redshift are labeled as having CL = 1. Identifications which were made based on colours that were consistent with a galaxy being at the absorption redshift, the proximity criterion, or photometric-redshift matches that were only marginally consistent with the absorption redshift are assigned confidence level CL = 2 or 3, with 2 being the more confident identification. No galaxy identification was possible for a few fields. For example, this may happen if an absorber redshift does not match the photometric redshift of any of the galaxies in a given field, or when galaxy colours are ambiguous or are consistent with a large redshift range. These fields are not assigned a CL value.

3.1 Examples

We now illustrate our process of absorbing galaxy identification with a few representative examples that include most of the issues we faced while assigning galaxies to absorption systems. The images and photometry for all objects in our sample are available on line at <http://enki.phyast.pitt.edu/Imaging.php>. We also provide results from photometric redshift and stellar population synthesis template fits, details of which are explained in the Appendix. Readers who are not interested in the details of galaxy selection can skip to §4.

Here we provide our reduced images, photometry tables, and photometric redshift fits and derived stellar population synthesis parameters for four fields. Sources detected within 100 kpc of the quasar sightline at the absorption redshift (or smallest absorption redshift for multiple absorbers along the same sightline) are numbered in order of increasing impact parameter from the quasar, and ellipses are drawn around sources in each image only to guide the eye. Photometry tables give positions relative to the quasar, AB magnitudes, and the detection significance, “DS”, which is defined as the number of standard deviations the source is detected above the background. $DS = S/(B \times N_{pix})$, where S is the net source counts, B is the counts per pixel that correspond to a source detected at 1σ above the background, and N_{pix} is the number of pixels within the detection isophote. A source is considered to be a detection if $DS \geq 2$ and $N_{pix} \geq 5$. Tables describing photometric redshift fits give details of the stellar population templates that best fit the photometry. The information provided includes object number as marked on the images and its projected distance from the quasar in arcsec and kpc assuming that the galaxy is at the absorption redshift, age of the stellar population, star formation rate e -folding time, τ , extinction, $E(B - V)$, metal mass fraction, Z ($Z_{\odot} = 0.2$), and the photometric redshift and error.

3.1.1 Example 1: the 0153+0009 field

This is an example of our highest level of confidence for absorbing galaxy identification, where the photometric red-

⁴ We sometimes used SDSS photometry to supplement our IR measurements. Details of our *photo-z* technique and the galaxy templates used are described in the Appendix.

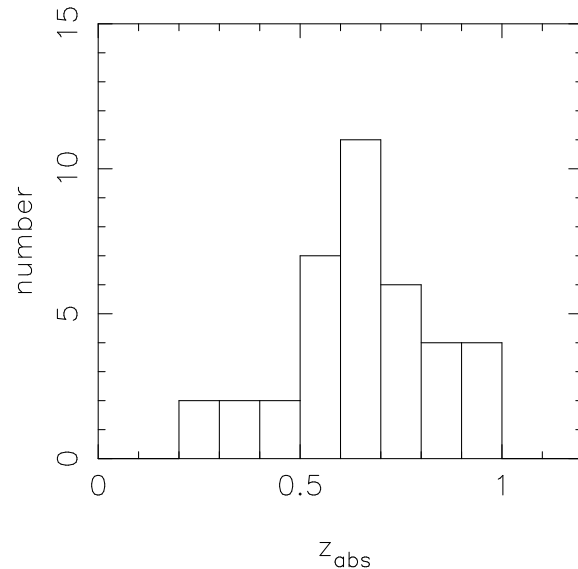


Figure 5. Redshift distribution of absorbers in quasar fields with K -band surface brightness limits between 21.5 and 22.5 magnitudes per square arcsec.

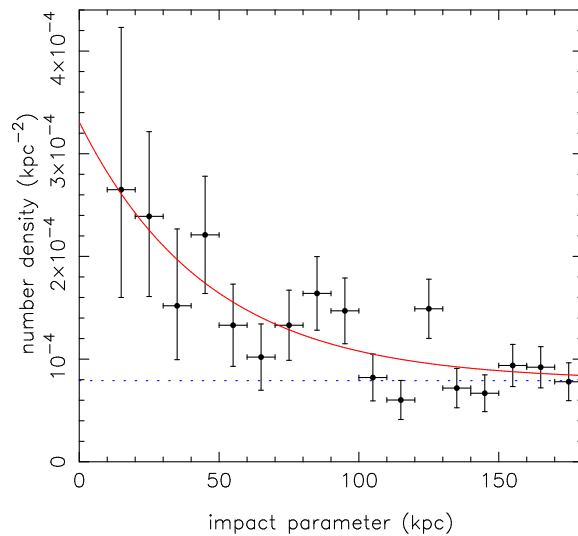


Figure 6. The number density of galaxies as a function of impact parameter from the quasar, calculated in annuli of width 10 kpc. Only K -band images with surface brightness limits between 21.5 and 22.5 magnitudes per square arcsec for absorbers between redshifts 0.5 and 0.8, where most of the absorption systems lie, were used. The red line is an exponential fit to the data points with an e-folding length of 46.1 kpc. The blue dotted line shows the background plus foreground galaxy number density of $7.9 \times 10^{-5} \text{ kpc}^{-2}$. The discrepant point at an impact parameter of ≈ 125 kpc notwithstanding, galaxies beyond ≈ 100 kpc can, statistically, be considered background or foreground galaxies that are not associated with the absorption system.

shift of the galaxy with the smallest impact parameter to the quasar matches the redshift of the absorption-line system.

The sightline towards the quasar 0153+0009 (SDSS J015318.19+000911.3) contains a subDLA system at $z_{\text{abs}} = 0.7714$ with a column density of $\log N_{\text{HI}} = 19.70^{+0.08}_{-0.10} \text{ cm}^{-2}$ (RTN06). We obtained J , H , and K images of this field (see Figure 7). We have used SDSS optical photometry for this field to supplement our infrared data; together the data were used to determine its photometric redshift. Our measured photometry is given in Table 2. The quasar PSF could not be subtracted as there were no suitable PSFs stars in the

field, and so the quasar has been masked out. We detect nine objects within 100 kpc of the quasar.

Object 1 is at $\theta = 4.9''$, which is equivalent to 36.6 kpc at the absorber redshift. SDSS photometry for Object 1 was obtained from S. Zibetti (private communication) since it is not in the “photoObj” catalogue made available in the SDSS database. S. Zibetti ran his PSF subtraction software on the SDSS image (Zibetti et al. 2007), and provided us with the photometry of Object 1 in all five SDSS bands (Table 3). A photometric redshift of $z_{\text{phot}} = 0.745 \pm 0.040$ is derived for Object 1 by supplementing these magnitudes with our infrared data (see Table 4). The stellar population

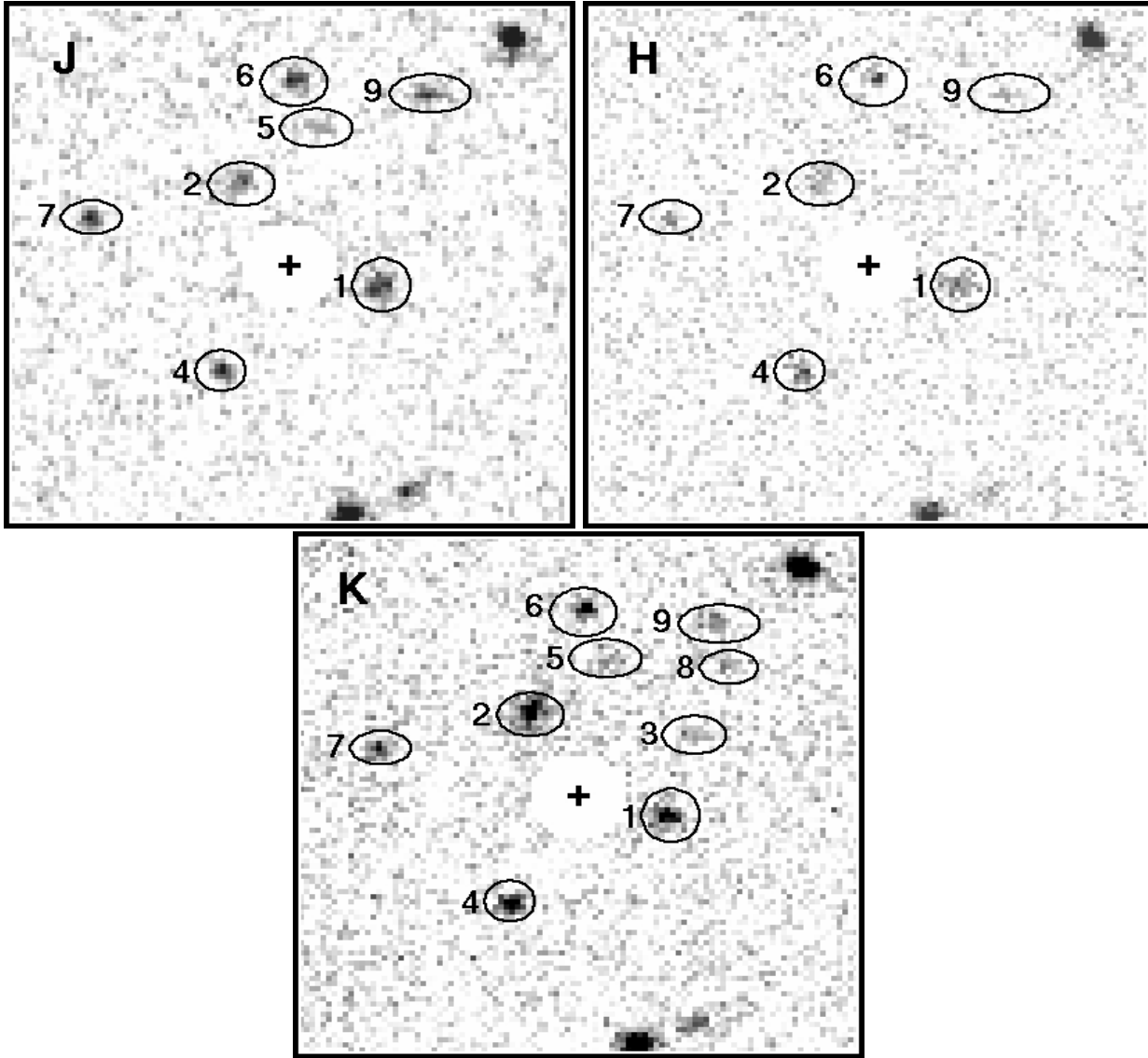


Figure 7. $30'' \times 30''$ J, H, K images of the 0153+0009 field. This field has a subDLA system at $z_{abs} = 0.7714$. As discussed in the text (§3.1.1), we identify Object 1 as the absorbing galaxy. The images shown above correspond to $\approx 222 \times 222$ kpc² at the absorber redshift. The quasar has been masked in all the frames, and its position is marked by a “+”. The quasar PSF could not be subtracted, as there were no suitable PSF stars in the field. North is up and east is to the left. Photometry for all labeled objects is given in Table 2. Ellipses are drawn only to guide the eye. Objects that are unmarked have impact parameters greater than 100 kpc, and are not considered to be candidate absorbers.

template fit is shown in Figure 8. This is consistent with the absorption redshift to within the errors, and therefore, Object 1 is considered to be the absorbing galaxy.

The $J - K = 1.38$ colour of Object 2 is not consistent with it being at the absorption redshift. Object 3 is included in the photometry table because it looks real by eye. However, based on its detection significance, DS , we do not consider it to be a confident detection. No redshift information could be extracted from the IR data on Objects 4, 5, and 8; they are not detected in the SDSS images.

Object 6 is identified as a star in the SDSS database, however, it is extended in our images. Objects 7 and 9 have $z_{phot} = 0.385 \pm 0.157$, and 0.073 ± 0.046 respectively, accord-

ing to the SDSS database⁵. The best-fit stellar population synthesis model to our IR photometry and SDSS optical photometry for Objects 6, 7, and 9 are shown in Figure 8, and the stellar population fit parameters are given in Table 4.

In summary, due to its matching photometric redshift as well as proximity, Object 1 is selected as the absorbing galaxy with $CL = 1$. The photometric redshift derived for Object 6 is consistent with the absorption redshift, making it likely that Objects 1 and 6 are members of the same galaxy cluster or group.

⁵ When available, the SDSS photometric redshift we report is `photozcc2` (Oyaizu et al. 2008), otherwise, the SDSS photometric redshift labeled “PhotoZ” is reported.

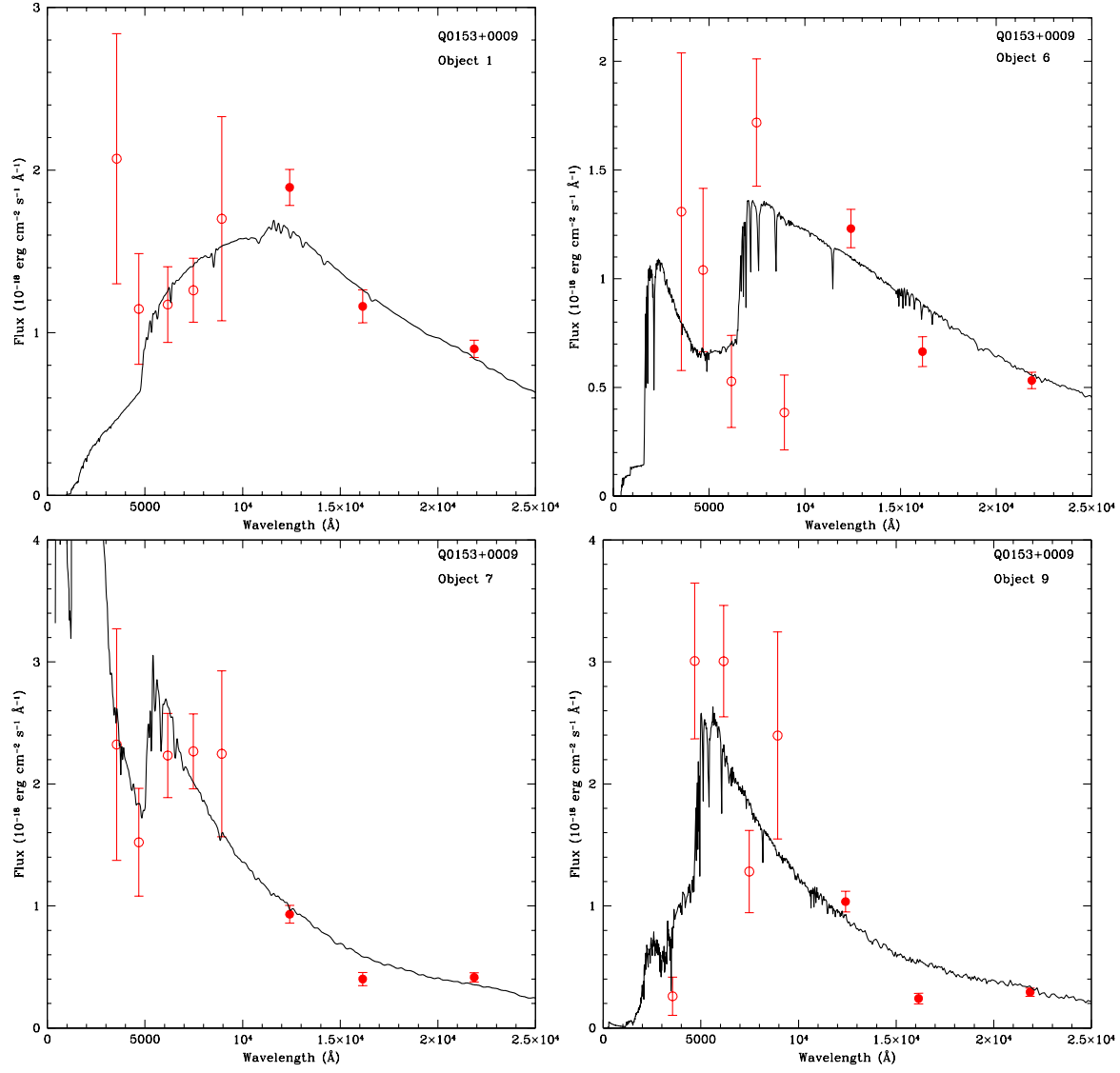


Figure 8. The curves are the best-fit stellar population synthesis models to the photometry for Objects 1, 6, 7, and 9 in the 0153+0009 field. The SDSS data are shown as open circles and our infrared photometric data, from Table 2, are shown as solid circles. See Table 4 for model details. As discussed in the text (§3.1.1), we identify Object 1 as the absorbing galaxy.

Table 2. 0153+0009: Infrared Photometry

Object	$\Delta\alpha^a$ "	$\Delta\delta^a$ "	θ^a "	$J \pm \sigma_J$	DS (N_{pix}) ^b	$H \pm \sigma_H$	DS (N_{pix}) ^b	$K \pm \sigma_K$	DS (N_{pix}) ^b
QSO	0.0	0.0	0.0	17.18 ± 0.003	31.9 (188)	17.58 ± 0.01	16.8 (120)	17.45 ± 0.004	20.5 (138)
1	−4.7	−1.4	4.9	21.43 ± 0.07	2.9 (41)	21.39 ± 0.10	2.7 (22)	21.01 ± 0.07	3.0 (35)
2	+2.5	+4.7	5.3	21.88 ± 0.09	2.3 (34)	21.82 ± 0.13	1.9 (21)	20.50 ± 0.05	2.7 (63)
3	−6.2	+3.4	7.1	...	...	...	...	23.22 ± 0.22	1.7 (8)
4	+3.6	−6.5	7.4	22.10 ± 0.08	2.9 (22)	21.55 ± 0.11	2.6 (20)	21.19 ± 0.07	3.5 (26)
5	−1.7	+7.7	7.9	23.09 ± 0.16	2.0 (13)	...	...	22.95 ± 0.21	2.0 (9)
6	−0.4	+10.8	10.8	21.90 ± 0.08	3.0 (26)	22.00 ± 0.12	2.9 (12)	21.58 ± 0.08	3.3 (19)
7	+10.8	+2.6	11.1	22.20 ± 0.09	2.9 (20)	22.54 ± 0.16	2.6 (8)	21.85 ± 0.10	2.6 (19)
8	−8.1	+7.6	11.1	...	...	...	...	23.12 ± 0.20	2.2 (7)
9	−7.3	+10.0	12.4	22.09 ± 0.09	2.6 (25)	23.10 ± 0.21	2.1 (6)	22.23 ± 0.13	2.2 (16)

^aRelative to the quasar.^bDS is the “detection significance”, and is defined as the number of sigma above the background that the source is detected. $DS = S/(B \times N_{pix})$, where S is the net source counts, B is the counts per pixel of a source that could be detected at 1σ above the background, and N_{pix} is the number of pixels within the detection isophote. A source is considered to be a detection if $DS \geq 2$ and $N_{pix} \geq 5$.**Table 3.** 0153+0009: Supplemental Photometry^a

Object 1	
$u' \pm \sigma_{u'}$	22.20±0.50
$g' \pm \sigma_{g'}$	24.30±0.38
$r' \pm \sigma_{r'}$	23.18±0.24
$i' \pm \sigma_{i'}$	22.24±0.18
$z' \pm \sigma_{z'}$	21.18±0.50

^aSDSS photometry provided by S. Zibetti, private communication.**Table 4.** 0153+0009: Photometric Redshift Fits^a

Galaxy		Stellar Population Synthesis Model Parameters					
#	θ^b "	b kpc	Age Gyr	τ Gyr	$E(B - V)$	Z	$z_{phot} \pm \sigma_{z_{phot}}$
1	4.9	36.6	12.0	5.00	1.00	0.0040	0.745±0.040
6	10.8	80.1	5.00	12.0	0.30	0.0004	0.745±0.113
7	11.1	82.1	3.00	3.00	0.00	0.0040	0.344±0.294
9	12.4	92.2	1.00	0.10	0.00	0.0080	0.244±0.157

^a $z_{abs} = 0.7714$ ^bRelative to the quasar

3.1.2 Example 2: the 0735+178 field

This is an example of a field where the three objects with the smallest impact parameters are ruled out as absorbing galaxy candidates. The fourth closest object is the best candidate for the absorbing galaxy.

The sightline towards the quasar 0735+178 contains a LLS at $z_{abs} = 0.4240$ with a column density $\log N_{HI} < 19$ cm^{-2} (RTN06). This is an interesting system because it has relatively strong Fe II $\lambda 2600$ and Mg I $\lambda 2852$ absorption (see RTN06). These systems generally tend to have higher HI column densities ($\log N_{HI} > 19$, RTN06), and therefore the identification of the galaxy causing this unusual absorption-line pattern might be illuminating. A complete optical and infrared set of images is available for this field. The images are shown in Figures 9 and 10. PSF subtractions were carried out on the optical data and no objects were detected within the subtracted region. The quasar PSF could not be subtracted on the infrared images as there were no suitable PSF stars in the field. Photometric measurements for the eight objects detected in this field are given in Tables 5 and 6.

Objects 1, 2, and 5 are in the SDSS database as having $z_{phot} = 0.662 \pm 0.057$, 0.451 ± 0.166 , and 0.238 ± 0.144 respectively. Stickel et al. (1993) obtained a spectrum of Object 1, and determined it to be at redshift $z = 0.645$. It is therefore ruled out as the absorber candidate. The best-fit stellar population synthesis models to our photometry for Objects 2, 4, and 8 are shown in Figure 11, and the best-fit template parameters are listed in Table 7. We derive a photometric redshift $z_{phot} = 0.878 \pm 0.038$ for Object 2, which is inconsistent with that listed in the SDSS database. The addition of infrared photometric measurements provides stronger constraints on the fit, making our redshift determination more reliable than that reported in the SDSS database. Object 3 is only detected in the infrared, and its $J - H = 0.29$ and $H - K = 0.81$ colours are not consistent with it being at the absorption redshift. We note that Object 3 has $R - K > 7.6$, which makes it an “extremely red object” (ERO). Object 4 is classified as a star in the SDSS database, however, it is extended on our images. The photometric redshift that we derive for Object 4 is consistent with the absorption redshift, and it is identified as the candidate absorber in this field. A stellar population synthesis model could not be fit to the photometry of Object 5 probably because of its low surface brightness and low detection significance in all our images. Its photometry is therefore highly uncertain.

In summary, Object 4 is selected as the absorbing galaxy in this field since its photometric redshift, 0.423 ± 0.179 , matches the absorption redshift, and the galaxies with smaller impact parameters are ruled out as candidate absorbers. This identification is assigned $\text{CL} = 1$.

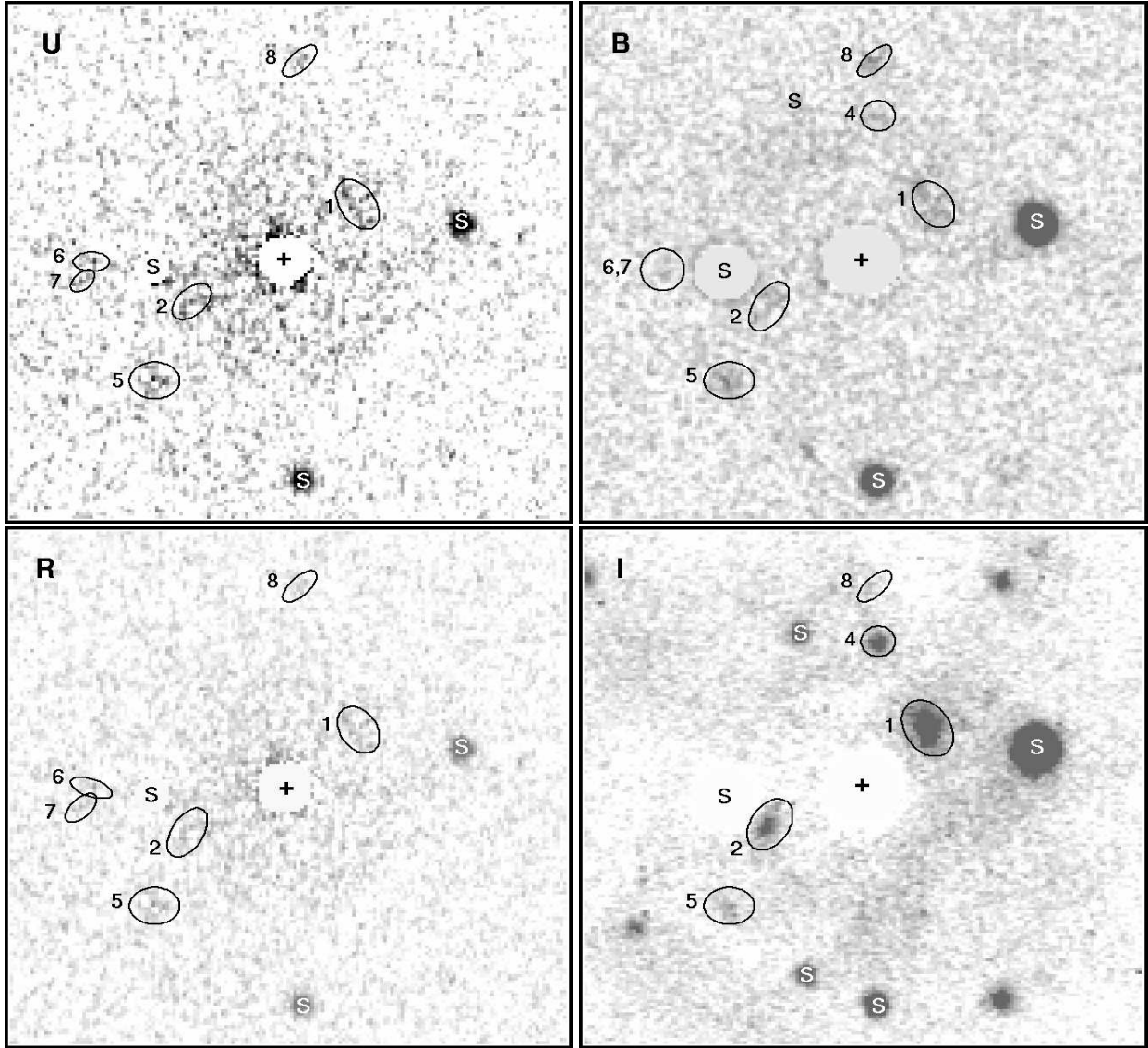


Figure 9. $44'' \times 44''$ PSF-subtracted U, B, R, I images of the 0735+178 field. This field has a LLS at $z_{abs} = 0.4240$. As discussed in the text (§3.1.2), we identify Object 4 as the absorbing galaxy. The images shown above correspond to $\approx 245 \times 245 \text{ kpc}^2$ at the absorber redshift. The central pixels of the quasar PSF subtraction residuals have been masked, and the position of its center is marked by a “+”. A nearby star, $10.9''$ east of the quasar, was also subtracted. All stars in the field are indicated by an “S”. North is up and east is to the left.

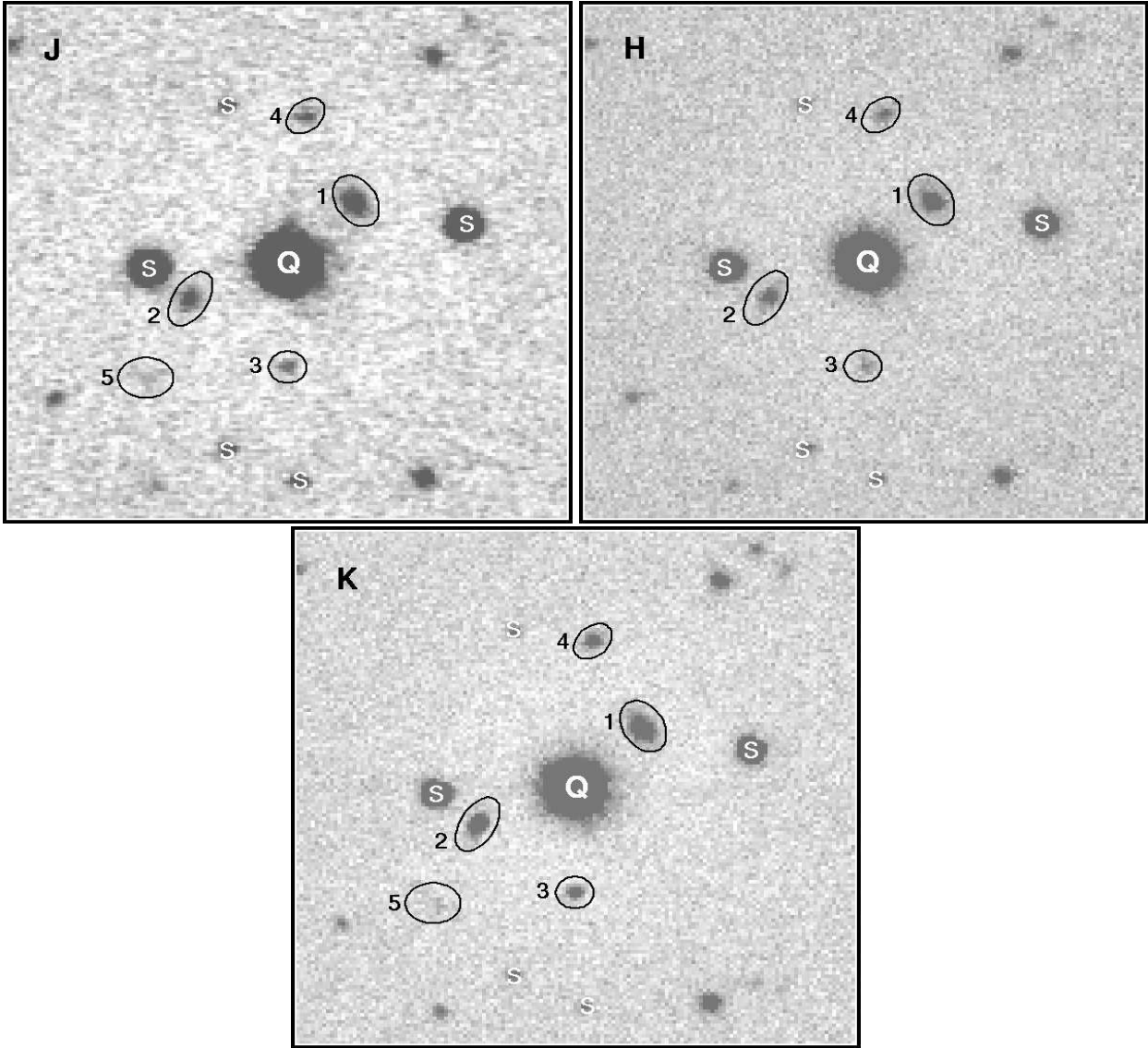


Figure 10. Same as Figure 9, but for *J*, *H*, and *K*. The quasar is marked by the letter “Q”. The quasar PSF could not be subtracted as there were no suitable PSF stars in the field. As discussed in the text (§3.1.2), we identify Object 4 as the absorbing galaxy.

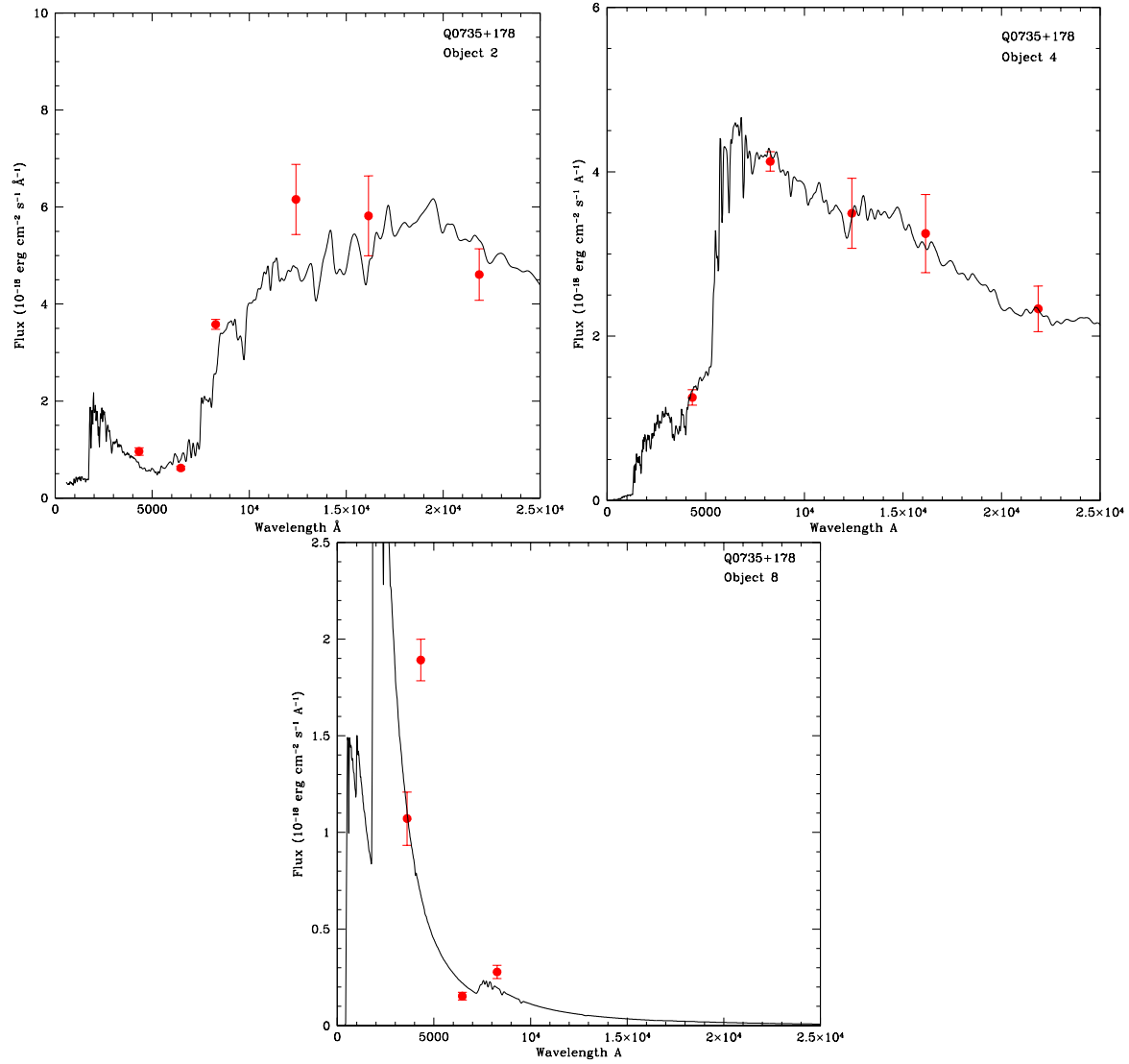


Figure 11. The curves are the best-fit stellar population synthesis models to our photometry (solid circles) for the objects in the 0735+178 field. See Table 7 for the model parameters. As discussed in the text (§3.1.2), we identify Object 4 as the absorbing galaxy.

Table 5. 0735+178: Optical Photometry

Object	$\Delta\alpha^a$ ''	$\Delta\delta^a$ ''	θ^a ''	$U \pm \sigma_U$	DS (N_{pix}) ^b	$B \pm \sigma_B$	DS (N_{pix}) ^b	$R \pm \sigma_R$	DS (N_{pix}) ^b	$I \pm \sigma_I$	DS (N_{pix}) ^b
QSO	+0.0	0.0	0.0	15.71 \pm 0.001	74.8 (2007)	15.50 \pm 0.001	138.8 (2187)	15.90 \pm 0.001	225.1 (1231)	15.20 \pm 0.001	37.7 (4057)
1	−5.2	+5.1	7.3	23.04 \pm 0.06	2.6 (67)	23.80 \pm 0.07	2.8 (51)	23.89 \pm 0.06	2.6 (67)	19.81 \pm 0.01	3.5 (633)
2	+7.7	−3.2	8.4	23.21 \pm 0.07	2.3 (66)	24.46 \pm 0.09	2.8 (28)	24.06 \pm 0.07	2.3 (66)	21.62 \pm 0.03	3.3 (125)
3	+0.1	−9.0	9.0	...	...	...	...	...	...	...	...
4	−1.4	+12.6	12.7	...	...	24.17 \pm 0.08	2.9 (36)	...	...	21.47 \pm 0.03	3.4 (140)
5	+10.8	−10.1	14.8	23.57 \pm 0.08	2.5 (43)	23.16 \pm 0.05	3.0 (86)	24.41 \pm 0.08	2.5 (43)	22.93 \pm 0.07	2.4 (52)
6	+15.6	+0.2	15.6	25.33 \pm 0.18	2.1 (10)	24.88 \pm 0.11	4.5 (12)	26.17 \pm 0.18	2.1 (10)	...	...
7	+16.4	−1.5	16.4	25.14 \pm 0.17	2.1 (12)	...	...	25.99 \pm 0.17	2.1 (12)	...	...
8	−1.0	+17.3	17.3	24.73 \pm 0.15	3.4 (11)	23.72 \pm 0.06	2.4 (66)	25.58 \pm 0.15	3.4 (11)	24.39 \pm 0.14	2.3 (14)

^aSame as for Table 2.

^bSame as for Table 2.

Table 6. 0735+178: Infrared Photometry

Object	$\Delta\alpha^a$ ''	$\Delta\delta^a$ ''	θ^a ''	$J \pm \sigma_J$	DS (N_{pix}) ^b	$H \pm \sigma_H$	DS (N_{pix}) ^b	$K \pm \sigma_K$	DS (N_{pix}) ^b
QSO	+0.0	0.0	0.0	14.04 \pm 0.13	116.3 (578)	13.58 \pm 0.16	116.3 (433)	13.35 \pm 0.13	142.8 (535)
1	−5.2	+5.1	7.3	19.40 \pm 0.13	4.3 (114)	18.99 \pm 0.16	4.1 (83)	18.66 \pm 0.13	5.6 (102)
2	+7.7	−3.2	8.4	20.15 \pm 0.14	3.6 (67)	19.64 \pm 0.17	3.7 (51)	19.24 \pm 0.13	6.4 (53)
3	+0.1	−9.0	9.0	21.31 \pm 0.15	3.3 (25)	21.02 \pm 0.19	2.6 (20)	20.21 \pm 0.14	4.9 (28)
4	−1.4	+12.6	12.7	20.77 \pm 0.14	3.4 (40)	20.27 \pm 0.17	3.4 (31)	19.98 \pm 0.14	4.3 (40)
5	+10.8	−10.1	14.8	21.88 \pm 0.18	2.1 (24)	...	...	22.17 \pm 0.21	2.5 (9)
6	+15.6	+0.2	15.6	...	...	...	...	...	...
7	+16.4	−1.5	16.4	...	...	...	...	...	...
8	−1.0	+17.3	17.3	...	...	...	...	...	...

^aSame as for Table 2.

^bSame as for Table 2.

Table 7. 0735+178: Photometric Redshift Fits^a

Galaxy		Stellar Population Synthesis Model Parameters					
#	θ^b ''	b kpc	Age Gyr	τ Gyr	$E(B - V)$	Z	$z_{phot} \pm \sigma_{z_{phot}}$
2	8.4	46.5	15.0	3.00	0.10	0.0500	0.878 \pm 0.038
4	12.7	70.5	0.50	0.10	0.30	0.0500	0.423 \pm 0.179
8	17.3	96.5	0.10	0.10	0.00	0.0001	0.959 \pm 0.644

^a $z_{abs} = 0.4240$

^bRelative to the quasar

3.1.3 Example 3: the 1109+0051 field

This field is not as straightforward as the previous ones. The sightline towards the quasar 1109+0051 (SDSS J110936.35+005111.3) contains two subDLA systems, one at $z_{abs} = 0.4181$ with a column density of $\log N_{HI} = 19.08^{+0.22}_{-0.38} \text{ cm}^{-2}$ and the other at $z_{abs} = 0.5520$ with a column density of $\log N_{HI} = 19.60^{+0.10}_{-0.12} \text{ cm}^{-2}$ (RTN06). Images of this field were obtained in g' , r' , J , H , and K , from which six objects are detected (Figures 12 and 13). The quasar PSF subtraction revealed no object within the subtracted region. The optical and infrared photometry are given in Tables 8 and 9, respectively.

Object 1 has an impact parameter $\theta = 1.3''$, which at the two absorber redshifts corresponds to 7 kpc and 8 kpc, respectively. It is detected in the g' , J , and H -bands. Since it overlaps with the quasar PSF, its photometry is uncertain. We consider it to qualify as a candidate absorber due to its proximity to the sightline. The best-fit stellar population synthesis models to our photometry for Objects 2, 3, 4, and 5 are shown in Figure 14, and the model parameters are tabulated in Table 10. The best-fit stellar population synthesis model to the photometry of Object 2 is only marginally consistent with (within 2σ of) the lower absorption redshift system, $z = 0.4181$. The photometry of Object 3 results in a photometric redshift of $z = 0.645 \pm 0.157$, which is consistent with the absorption system at $z_{abs} = 0.5520$. However, as can be seen from Table 10, the photometric redshift we derive for Object 4, while inconsistent with the SDSS-derived photometric redshift of 0.138 ± 0.044 , is consistent with both absorption redshifts. In addition, the redshift derived for Object 5 is consistent with the absorption system at $z_{abs} = 0.4181$ (but inconsistent with the SDSS redshift of 0.280 ± 0.063). Therefore, Objects 1, 3, 4, and 5 are all potential absorber candidates for the absorption systems in this field, while Object 2 is marginally consistent at the lower redshift. Given this ambiguity, we use the proximity criterion as the deciding factor, and select Object 1 as the $z_{abs} = 0.4181$ candidate and Object 3 as the $z_{abs} = 0.5520$ candidate, both with confidence level $CL = 2$.

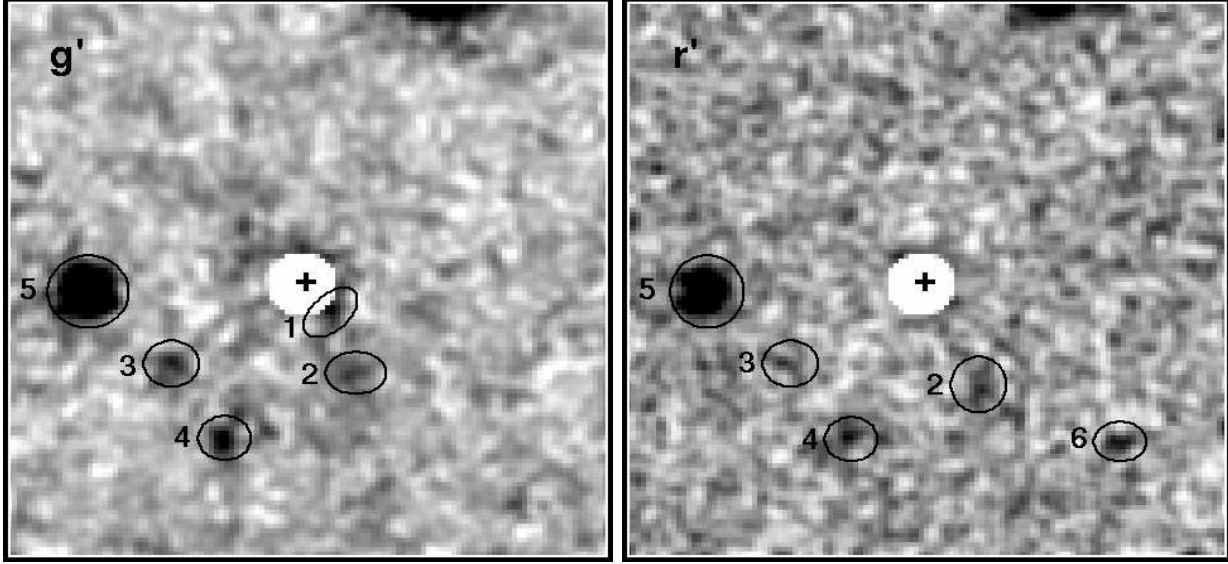


Figure 12. $36'' \times 36''$ PSF-subtracted g' and r' images of the 1109+0051 field. This field has two subDLA systems, one at $z_{abs} = 0.4180$ and the other at $z_{abs} = 0.5520$. As discussed in the text (§3.1.3), we identify Object 1 as the absorbing galaxy at $z_{abs} = 0.4180$ and Object 3 as the absorbing galaxy at $z_{abs} = 0.5520$. The images shown above correspond to $\approx 199 \times 199 \text{ kpc}^2$ and $\approx 231 \times 231 \text{ kpc}^2$ at the two redshifts, respectively. The frames are smoothed to bring out LSB features. The PSF residuals have been masked. The quasar position is marked by a "+". North is up and east is to the left.

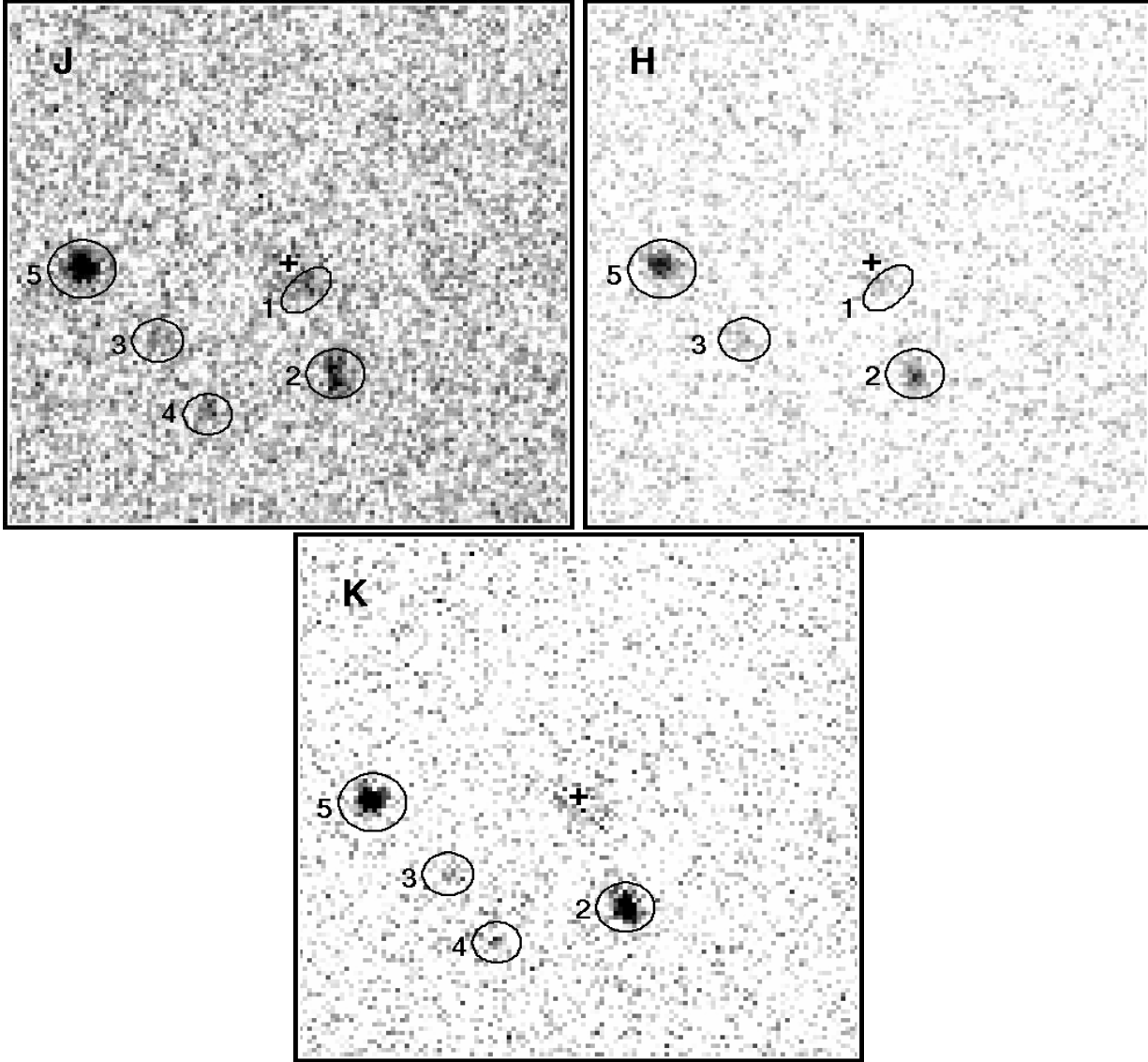


Figure 13. Same as Figure 12, but for *J*, *H*, and *K*. There is evidence for Object 1 in the *K* frame, however, it does not meet the “5 contiguous pixels above 1σ ” detection criterion. As discussed in the text (§3.1.3), we identify Object 1 as the absorbing galaxy at $z_{abs} = 0.4180$ and Object 3 as the absorbing galaxy at $z_{abs} = 0.5520$.

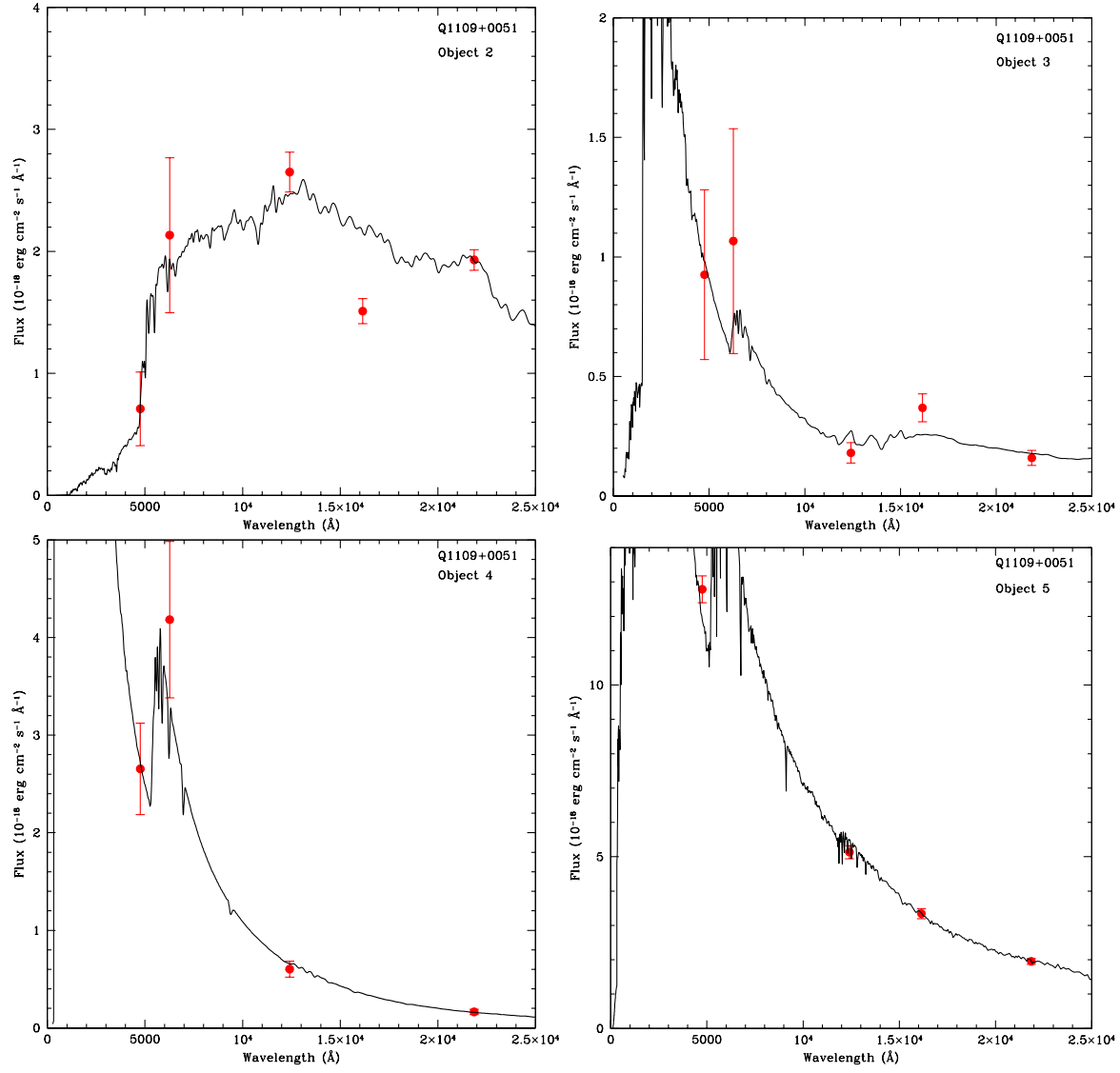


Figure 14. The curves are the best-fit stellar population synthesis models to our photometry (solid circles) for objects in the 1109+0051 field. The best-fit parameters are listed in Table 10. As discussed in the text (§3.1.3), we identify Object 3 as the absorbing galaxy at $z_{abs} = 0.5520$.

Table 8. 1109+0051: Optical Photometry

Object	$\Delta\alpha^a$ ''	$\Delta\delta^a$ ''	θ^a ''	$g' \pm \sigma_{g'}$	DS (N_{pix}) ^b	$r' \pm \sigma_{r'}$	DS (N_{pix}) ^b
QSO	0.0	0.0	0.0	18.45 ± 0.03	29.5 (422)	18.45 ± 0.05	9.1 (263)
1	-0.6	-1.1	1.3	23.79 ± 0.33	2.6 (26)	...	...
2	-3.4	-7.4	8.1	24.58 ± 0.64	2.6 (12)	22.79 ± 0.42	2.7 (14)
3	+8.4	-5.4	10.0	24.29 ± 0.56	2.6 (16)	23.54 ± 0.67	2.3 (8)
4	+4.6	-9.9	10.9	23.15 ± 0.24	3.8 (34)	22.05 ± 0.27	3.8 (20)
5	+13.4	-0.7	13.4	21.44 ± 0.07	4.8 (142)	20.52 ± 0.10	3.0 (111)
6	-11.7	-10.6	15.8	...	...	22.85 ± 0.42	2.2 (16)

^aSame as for Table 2.

^bSame as for Table 2.

Table 9. 1109+0051: Infrared Photometry

Object	$\Delta\alpha^a$ ''	$\Delta\delta^a$ ''	θ^a ''	$J \pm \sigma_J$	DS (N_{pix}) ^b	$H \pm \sigma_H$	DS (N_{pix}) ^b	$K \pm \sigma_K$	DS (N_{pix}) ^b
QSO	0.0	0.0	0.0	18.06 ± 0.01	12.8 (151)	18.41 ± 0.01	9.1 (113)	18.03 ± 0.01	10.8 (119)
1	-0.6	-1.1	1.3	22.24 ± 0.13	2.6 (16)	22.36 ± 0.17	2.1 (13)	...	...
2	-3.4	-7.4	8.1	21.07 ± 0.07	2.6 (47)	21.10 ± 0.08	2.5 (34)	20.18 ± 0.05	3.2 (55)
3	+8.4	-5.4	10.0	23.98 ± 0.29	1.7 (5)	22.63 ± 0.19	2.1 (10)	22.88 ± 0.23	2.4 (6)
4	+4.6	-9.9	10.9	22.67 ± 0.16	2.0 (14)	...	...	22.86 ± 0.21	2.5 (6)
5	+13.4	-0.7	13.4	20.35 ± 0.04	3.5 (67)	20.24 ± 0.05	3.2 (59)	20.17 ± 0.05	3.3 (55)
6	-11.7	-10.6	15.8	...	...	...	...	...	...

^aSame as for Table 2.

^bSame as for Table 2.

Table 10. 1109+0051: Photometric Redshift Fits^a

Galaxy		Stellar Population Synthesis Model Parameters					
#	θ^b ''	b kpc	Age Gyr	τ Gyr	$E(B - V)$	Z	$z_{phot} \pm \sigma_{z_{phot}}$
2	8.1	44.7	0.50	0.10	0.50	0.0500	0.266±0.109
3	10.0	55.4	0.10	12.0	0.20	0.0500	0.645±0.157
4	10.9	60.4	1.00	1.00	0.00	0.0001	0.433±0.222
5	13.4	73.9	1.00	12.0	0.10	0.0080	0.388±0.050

^a $z_{abs} = 0.4181, 0.5520$

^bRelative to the quasar

3.1.4 Example 4: the 1715+5747 field

This is a case where no galaxy is identified as the absorber. The sightline towards the quasar 1715+5747 (SDSS J171539.86+574722.2) contains a subDLA system at $z_{abs} = 0.5579$ with a column density of $\log N_{HI} = 19.18^{+0.15}_{-0.18} \text{ cm}^{-2}$ (RTN06). A complete optical and infrared dataset was obtained for this field. Figures 15 and 16 show that only three objects are detected within 100 kpc of the quasar at z_{abs} . PSF subtractions were carried out on the optical images and no objects were detected within the subtracted region. The quasar PSF could not be subtracted on the infrared images as there were no suitable PSF stars in the field. Object 1 is located $3.5''$ from the quasar sightline which corresponds to 22.3 kpc at the absorption redshift. Objects 2 and 3 have $z_{phot} = 0.621 \pm 0.085$ and 0.398 ± 0.053 , respectively, according to the SDSS database.

The best-fit stellar population synthesis model to our photometry for Objects 1, 2, and 3 are shown in Figure 17, and the model parameters are listed in Table 13. The photometric redshift we derive for Object 1 does not match the absorption redshift. While the SDSS photometric redshift for Object 2 is consistent with the redshift of the absorption system and our optical photometric measurements agree well with those measured by the SDSS, the addition of our IR data results in a very different photometric redshift for Object 2. Again, as was the case for Object 2 in the 0735+178 field, the addition of IR data was crucial for the determination of the galaxy's redshift. With regards to Object 3, we derive a photometric redshift that is consistent with the one obtained by the SDSS.

Thus, none of the objects detected in this field have photometric redshifts consistent with the absorption redshift. Based on their proximity to the quasar sightline, one might expect either Object 1 or 2 to be the absorbing galaxy. However, until spectroscopic data or better photometry are available that might prove our results to be incorrect, we consider our data on this field to be inconclusive, i.e., we do not have an absorbing galaxy identification. It may be one of the cases where the absorbing galaxy is $< 0.8''$ (5.2 kpc) from the quasar sightline, or at a larger impact parameter and fainter than the brightness limit of our K -band data, $L_K = 0.09L_K^*$.

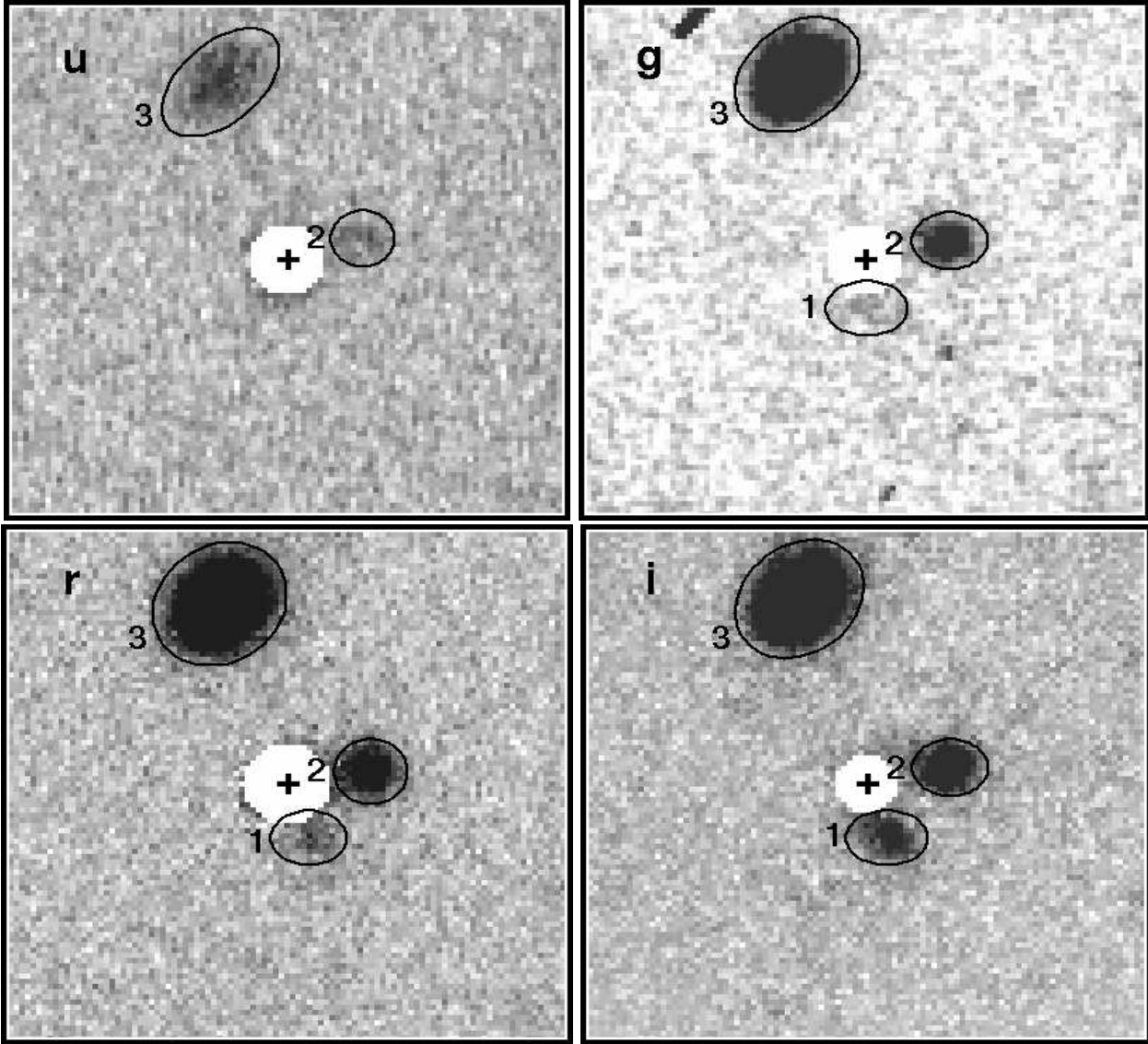


Figure 15. $30'' \times 30''$ PSF subtracted u', g', r', i' images of the field 1715+5747. This field has a subDLA system at $z_{abs} = 0.5579$. None of the three objects in this field is a galaxy at the absorption redshift, and so the absorber galaxy in this field remains unidentified (§3.1.4). The image shown above corresponds to $\approx 220 \times 220$ kpc² at the absorber redshift. The quasar PSF subtraction residuals have been masked, and the position of the quasar is marked by a “+”. The track northeast of Object 3 is a cosmic ray as are the two sources south and southwest of Object 1 in the g' -band image. North is up and east is to the left.

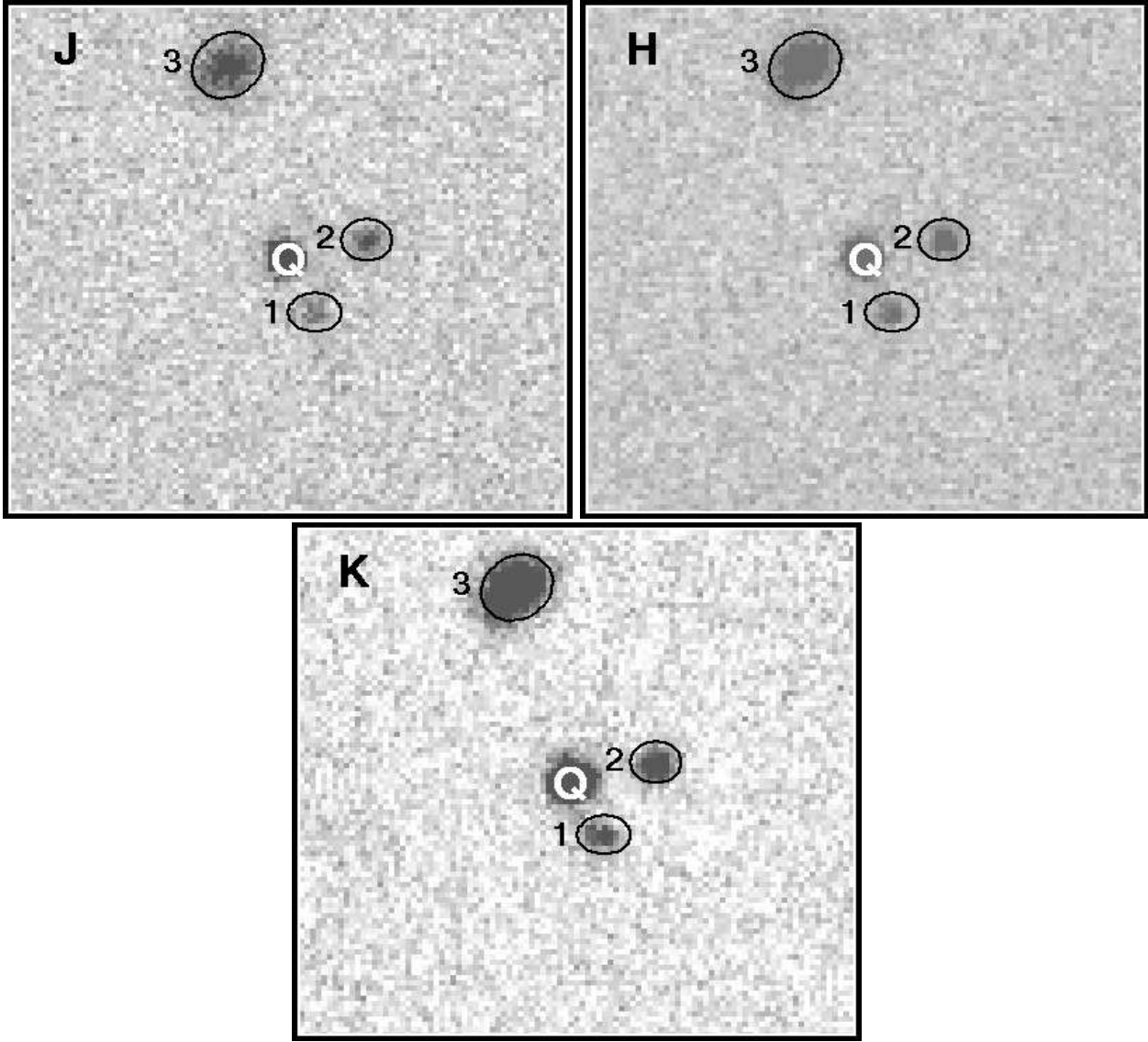


Figure 16. $30'' \times 30''$ *J*, *H*, *K* images of the field 1715+5747. This field has a subDLA system at $z_{abs} = 0.5579$. None of the three objects in this field is a galaxy at the absorption redshift, and so the absorber galaxy in this field remains unidentified (§3.1.4). The images shown above correspond to $\approx 220 \times 220$ kpc² at the absorber redshift. The quasar is marked by the letter “Q”. The quasar PSF could not be subtracted as there were no suitable PSF stars in the field. North is up and east is to the left.

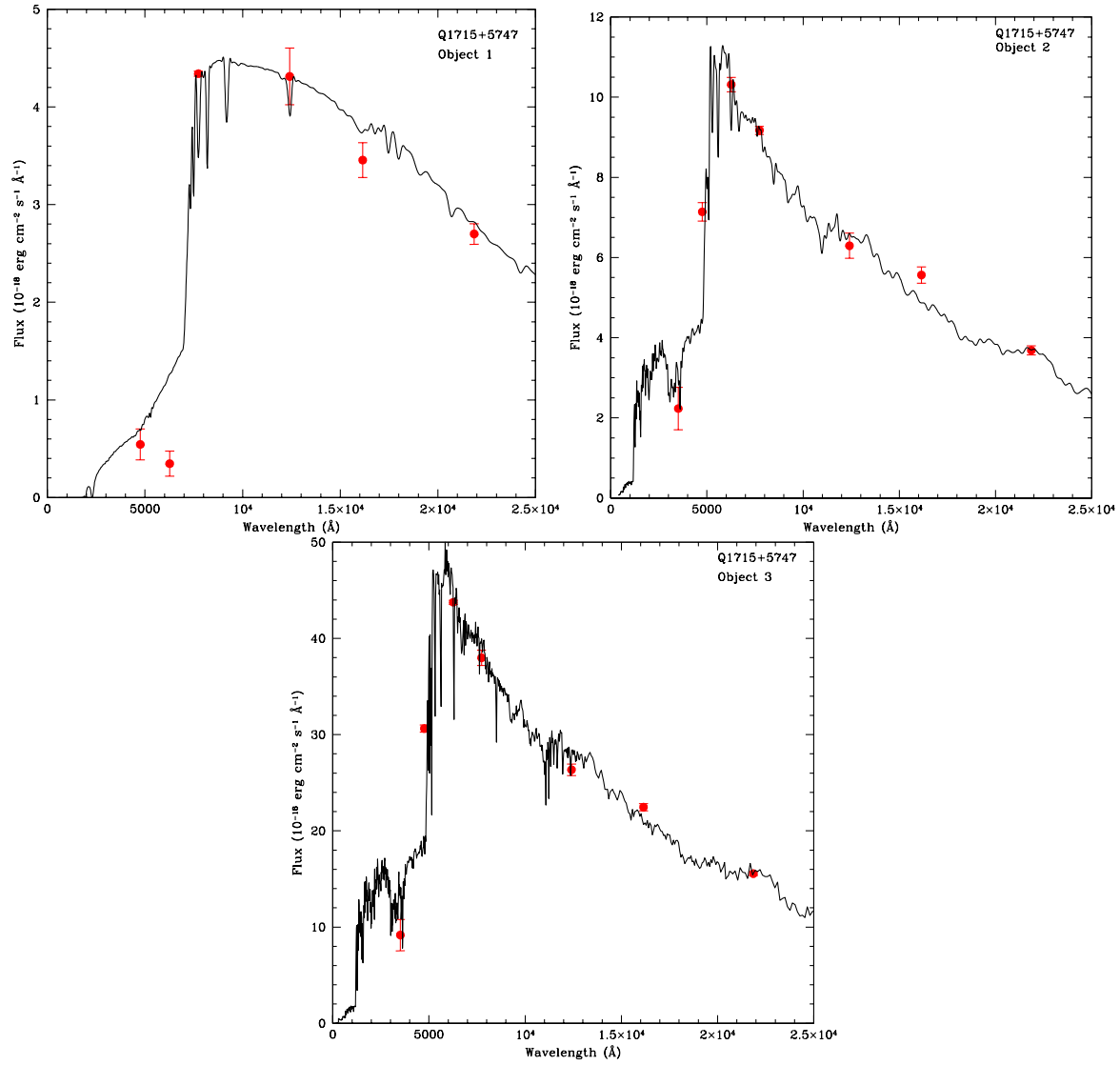


Figure 17. The curves are the best-fit stellar population synthesis models to our photometry (solid circles) for Objects in the 1715+5747 field. The best-fit model parameters are listed in Table 13. None of the three galaxies is at the absorption redshift (§3.1.4)

Table 11. 1715+5747: Optical Photometry

Object	$\Delta\alpha_{''}^a$	$\Delta\delta_{''}^a$	$\theta_{''}^a$	$u' \pm \sigma_{u'}$	DS (N_{pix}) ^b	$g' \pm \sigma_{g'}$	DS (N_{pix}) ^b	$r' \pm \sigma_{r'}$	DS (N_{pix}) ^b	$i' \pm \sigma_{i'}$	DS (N_{pix}) ^b
QSO	0.0	0.0	0.0	19.69 ± 0.15	21.9 (496)	18.21 ± 0.04	40.5 (758)	18.44 ± 0.04	18.4 (770)	18.55 ± 0.05	20.5 (424)
1	−1.4	−3.2	3.5	...	...	24.87 ± 0.41	2.1 (34)	24.76 ± 0.53	2.0 (21)	21.56 ± 0.08	3.5 (160)
2	−4.3	+0.9	4.4	23.99 ± 0.27	2.7 (78)	22.07 ± 0.07	4.1 (224)	21.07 ± 0.05	4.4 (282)	20.74 ± 0.06	5.0 (230)
3	+3.2	+11.1	11.5	22.46 ± 0.19	3.3 (266)	20.49 ± 0.05	8.4 (456)	19.51 ± 0.04	8.4 (630)	19.20 ± 0.05	8.8 (539)

^aSame as for Table 2.

^bSame as for Table 2.

Table 12. 1715+5747: Infrared Photometry

Object	$\Delta\alpha_{''}^a$	$\Delta\delta_{''}^a$	$\theta_{''}^a$	$J \pm \sigma_J$	DS (N_{pix}) ^b	$H \pm \sigma_H$	DS (N_{pix}) ^b	$K \pm \sigma_K$	DS (N_{pix}) ^b
QSO	0.0	0.0	0.0	18.07 ± 0.01	11.8 (82)	17.82 ± 0.01	12.2 (103)	17.28 ± 0.01	16.0 (139)
1	−1.4	−3.2	3.5	20.54 ± 0.08	2.8 (35)	20.21 ± 0.06	3.4 (41)	19.82 ± 0.04	3.2 (68)
2	−4.3	+0.9	4.4	20.13 ± 0.06	3.2 (46)	19.69 ± 0.04	3.7 (61)	19.48 ± 0.03	4.0 (74)
3	+3.2	+11.1	11.5	18.57 ± 0.03	3.5 (174)	18.17 ± 0.02	4.6 (196)	17.92 ± 0.01	5.0 (249)

^aSame as for Table 2.

^bSame as for Table 2.

Table 13. 1715+5747: Photometric Redshift Fits^a

Galaxy		Stellar Population Synthesis Model Parameters					
#	$\theta_{''}^b$	b	Age	τ	$E(B - V)$	Z	$z_{phot} \pm \sigma_{z_{phot}}$
	''	kpc	Gyr	Gyr			
1	3.5	22.3	1.00	0.10	0.50	0.0001	0.890±0.066
2	4.4	28.6	0.50	0.10	0.20	0.0500	0.287±0.044
3	11.5	74.4	0.50	0.10	0.20	0.0500	0.341±0.107

^a $z_{abs} = 0.5579$

^bRelative to the quasar

4 GALAXY PROPERTIES

4.1 Earlier work

Absorber galaxies that had been previously identified are presented in Table 14. The first results from our DLA imaging programme that were presented in Turnshek et al. (2001) and Rao et al. (2003) are included in this table. Additionally, our current sample (Table 1) has five fields that were studied by other investigators, however, our new images did not alter the earlier conclusions. These five are also included in Table 14 with previous studies referenced.

Mg II absorbers from RTN06 are tabulated in the first section of Table 14, and those not in RTN06 are included in the second section of the table. Column 1 is the quasar designation, column 2 gives the quasar emission redshift, columns 3 and 4, the Mg II absorption redshift and rest equivalent width, and column 5, the H I column density of the absorber. Column 6 gives the impact parameter of the identified galaxy in kpc, and columns 7 and 8 give the galaxy's AB magnitude and absolute luminosity with respect to L^* (see §4.2). The relevant filter is noted in parentheses. The reference for the galaxy's parameters is given in column 9 and the method by which it was identified is given in column 10. "Specz" indicates that a spectroscopic redshift was used to identify the galaxy, "Photoz" indicates that the galaxy's photometric redshift matched the absorption redshift, and "Prox" indicates that the closest galaxy to the quasar sight-line was chosen as the absorbing galaxy. Column 11 indicates the confidence level, CL, assigned to the identification (see §3). "Photoz" and "Prox" identifications are assigned CL = 1 and CL = 2, respectively. Specz is assigned CL = 1, except for the $z_{abs} = 0.656$ galaxy in the 1622+239 field. Steidel et al. (1997) obtained a spectroscopic redshift that matches z_{abs} for the galaxy at $b = 99.6$ kpc in this field, but commented that a galaxy this faint and this far away could not be the DLA absorber. More recently, Kacprzak et al. (2007) have identified this galaxy as the absorber in their work, and we have adopted this new interpretation as well. However, we have assigned this galaxy an identification confidence level of CL = 2, because we feel that we cannot be as confident about the validity of this identification as we are about the rest of the spectroscopically-identified galaxy candidates (also see §6).

Table 14. Absorbing Galaxy Identifications (*Previously known*)

Quasar	z_{em}	z_{abs}	$W_0^{\lambda 2796}$ (Å)	$\log N_{HI}$ (cm ⁻²)	Impact par. b (kpc)	m_{AB} ^a	L/L^*	Ref. ^b	ID Method	CL
MgII Systems from RTN06:										
0002+051	1.899	0.8514	1.09	19.08	25.9	22.90(R) ^c	0.92	1	Specz	1
0058+019	1.959	0.6127	1.666 ^d	20.04	7.3	23.7(R)	0.17	2,3	Specz	1
0117+213	1.491	0.5764	0.91	19.15	7.3	... ^e	2.54	4	Specz	1
0302-223	1.409	1.0096	1.16	20.36	25.8 ^f	24.56(R)	0.22	5,6	Specz	1
0420-014	0.915	0.6331	0.75 ^d	18.54	14.6	... ^e	0.34	4	Specz	1
0454+039	1.343	0.8596	1.45	20.67	5.5	24.76(R)	0.14	4,5	Specz	1
0738+313	0.630	0.2213	0.61	20.90	19.2	19.7(K)	0.10	7	Specz	1
0827+243	0.941	0.5247	2.563 ^g	20.30	32.8	18.97(K)	1.20	8,9	Specz	1
0952+179	1.478	0.2377	1.087 ^d	21.32	4.2	22.10(K)	0.01	8	Prox	2
1038+064	1.265	0.4416	0.66	18.30	56.0	21.26(R) ^c	0.29	10	Specz	1
1127-145	1.187	0.3130	2.21	21.71	45.6	19.26(I)	0.59	1,8	Specz	1
1148+386	1.304	0.5533	0.482 ^g	<18	20.3	21.50(R) ^c	0.48	10	Specz	1
1209+107	2.193	0.3930	1.00	19.46	34.9	22.22(R)	0.14	5	Specz	1
1229-021	1.038	0.7571	0.384 ^g	18.36	10.5	25.66(R)	0.02	5,11	Prox	2
1241+176	1.282	0.5505	0.570 ^g	18.90	21.4	21.96(R) ^c	0.31	10	Specz	1
1317+277	1.014	0.6601	0.34	18.57	103.2	21.91(R) ^c	0.61	10	Specz	1
1622+239	0.927	0.6561	1.471 ^g	20.36	99.6	22.67(K)	0.05	10,12 ^h	Specz	2
...	...	0.8913	1.622 ^g	19.23	21.4	21.43(K)	0.65	12	Specz	1
1623+269	2.521	0.8881	1.214 ^g	18.66	48.2	24.20(R) ^c	0.21	10	Specz	1
1629+120	1.792	0.5313	1.666 ^g	20.70	17.1	19.55(K)	1.04	8	Photoz	1
2128-123	0.501	0.4297	0.41	19.18	48.8	20.98(R) ^c	0.35	10	Specz	1
Others:										
0051+0041	1.189	0.7397	2.4	20.4	24.1	22.45(I)	0.41	13	Specz	1
0151+045	0.404	0.1602	1.55	19.84	17.7	19.31(R)	0.14	14	Specz	1
0235+164	0.940	0.5243	2.42	21.70	13.1	20.2(I)	0.72	3	Specz	1
0439-433	0.593	0.1009	1.62	19.85	7.6	17.2(I)	0.98	3	Specz	1
0809+483	0.871	0.4369	2.00	20.80	8.4	19.9(I)	0.59	3	Specz	1
1122-1649	2.400	0.6850	1.83	20.45	25.2	22.4(I)	0.35	3,15	Photoz	1
1137+3907	1.027	0.7195	3.0	21.1	10.8	19.8(K)	0.16	13	Specz	1
1229-021	1.038	0.3950	2.22	20.75	7.5	22.31(R)	0.08	5	Prox	2

^a All quantities have been converted to the “737” cosmology.

^b 1. Kacprzak et al. 2010, 2. Pettini et al. 2000, 3. Chen et al. 2005, 4. Churchill et al. 1996, 5. Le Brun et al. 1997, 6. Peroux et al. 2010, 7. Turnshek et al. 2001, 8. Rao et al. 2003, 9. Steidel et al. 2003, 10. Kacprzak et al. 2007, 11. Steidel et al. 1994, 12. Steidel et al. 1997, 13. Lacy et al. 2003, 14. Guillemin & Bergeron 1997, 15. Mshar et al. 2007

^c The $m(F702W)$ magnitudes provided by Kacprzak et al. (2007; 2010) has been converted to an $R(AB)$ magnitude.

^d Measurements of $W_0^{\lambda 2796}$ have been changed from RTN06 values to reflect the more recent measurements of Mathes et al. (in preparation).

^e Magnitude not provided by Churchill et al. 1996.

^f We have taken Object #4, as labeled in Le Brun et al. (1997) and Peroux et al. (2010), as the absorber.

^g Measurements of $W_0^{\lambda 2796}$ have been changed from RTN06 values to reflect the more recent measurements of Quider et al. (2011).

^h Steidel et al. (1997) obtained a spectroscopic redshift that matches z_{abs} for the galaxy at $b = 99.6$ kpc, but commented that a galaxy this faint and this far away could not be the DLA absorber. However, Kacprzak et al. (2007) have adopted this galaxy as the absorber in their work. We have adopted this new interpretation as well, but have assigned it CL = 2 (see text).

4.2 Current work

Table 15 provides details on DLA candidate galaxies in the 55 quasar fields that appear here for the first time. The first five columns are as described above for Table 14. We note here that column density values less than 10^{19} cm^{-2} were obtained by fitting Voigt profiles with the same Doppler broadening parameter as the stronger subDLA and DLA lines (Rao & Turnshek 2000; RTN06). The column densities should therefore be considered approximate, but less than 10^{19} cm^{-2} . Nevertheless, these are legitimate Mg II absorption systems for which absorbing galaxies have been identified. Column 6 gives the object in each field that was identified as the absorbing galaxy candidate. As indicated in §3, the numbering is in order of increasing distance from the quasar sightline. Columns 7 and 8 are the galaxy's impact parameter in arcsec and kpc, respectively, and column 9 gives the galaxy's photometric redshift and associated error, which were determined if the field was observed through four or more filters.

Columns 10 and 11 give the galaxy's AB magnitude and absolute luminosity with respect to L^* . K -band AB magnitudes and luminosities are provided unless the object was not observed (or detected) in K , in which case the non- K filter is noted. Our magnitude errors are typically 10 to 20%. See, for example, the photometry tables of individual fields in §3.

The following M^* values were used to determine L/L^* values for the galaxies listed in Tables 14 and 15 in the filters indicated:

$$\begin{aligned} M_B^* &= -21.22 \text{ (} 0.1 < z < 0.5, \text{ Dahlen et al. 2005)} \\ M_B^* &= -21.46 \text{ (} 0.5 < z < 1.0, \text{ Dahlen et al. 2005)} \\ M_g^* &= -21.47 \text{ (} 0.45 < z < 0.81, \text{ Gabasch et al. 2004)} \\ M_g^* &= -21.72 \text{ (} 0.81 < z < 1.11, \text{ Gabasch et al. 2004)} \\ M_R^* &= -22.38 \text{ (Dahlen et al. 2005)} \\ M_r^* &= -22.12 \text{ (} 0.4 < z < 0.8, \text{ Wolf et al. 2003)} \\ M_i^* &= -23.4 \text{ (} z = 1, \text{ Ilbert et al. 2005)} \\ M_i^* &= -22.17 \text{ (} 0.6 < z < 0.8, \text{ Ilbert et al. 2005)} \\ M_j^* &= -22.68 \text{ (} 0.1 < z < 0.5, \text{ Dahlen et al. 2005)} \\ M_j^* &= -23.09 \text{ (} 0.75 < z < 1.0, \text{ Dahlen et al. 2005)} \\ M_H^* &= -22.93 \text{ (Jones et al. 2006; assuming no evolution between } z = 0.1 \text{ and } 0.5) \\ M_K^* &= -22.86 \text{ (Cirasuolo et al. 2006)} \end{aligned}$$

K -corrections for galaxies whose redshifts were obtained using template fits to the photometry were determined from the template fits themselves. For the rest, an Sb-type K -correction in the observed filter at the redshift of the absorber was assumed.

Columns 12 and 13 give the method by which the DLA galaxy candidate was identified, and CL, the confidence level of this identification (§3). Of the 66 absorbers in Table 15, 17 have photometric redshifts that match the absorption redshift, and are assigned CL = 1. Thirty-seven identifications were made either with colours that were consistent with the galaxy being at the absorption redshift, the proximity criterion, or photometric-redshift matches that were only marginally consistent with the absorption redshift. These are labeled as having CL = 2 or 3, with 2 being the more confident identification. No galaxy identification was possible for 12 absorbers. Examples of some of these were given in §3.

Table 16. Spearman Rank Correlation Test Results

Parameters	r_S	$P(r_S)$	N_σ
$z_{abs}, W_0^{\lambda 2796}$	0.10	0.390	0.9
$z_{abs}, \log N_{HI}$	-0.02	0.875	0.2
z_{abs}, b	0.18	0.103	1.6
$z_{abs}, L/L^*$	0.19	0.089	1.7
$W_0^{\lambda 2796}, \log N_{HI}$	0.53	5.1E-7	4.7
$W_0^{\lambda 2796}, b$	-0.21	0.068	1.8
$W_0^{\lambda 2796}, L/L^*$	0.09	0.419	0.8
$\log N_{HI}, L/L^*$	0.07	0.526	0.7
$\log N_{HI}, b$	-0.34	0.002	3.0
$b, L/L^*$	0.14	0.230	1.2

Figure 18 shows that the CL = 1 and CL = 2 or 3 samples have very similar impact parameter and luminosity distributions. Here, we have included galaxies from Tables 14 and 15. In Figure 18, impact parameter, b , is plotted versus log H I column density for the 80 galaxies that have b and L measurements. Galaxy luminosity is represented by the size of the symbol (see caption). We will discuss the b -log N_{HI} plane in more detail later, however, this plot clearly shows that the CL values do not cluster with either parameter, or with luminosity. In addition, Kolmogorov-Smirnov (KS) tests show that the two CL samples are drawn from the same parent population: the KS test probabilities are 0.08 for the two luminosity distributions, 0.68 for the two impact parameter distributions, and 0.94 for the two H I column density distributions. Therefore, this is evidence that we are *statistically* selecting similar candidate galaxies in all of these samples. Hereafter, we will no longer separate the sample by CL value, and will explore the properties of all candidate galaxies irrespective of their identification method.

Our galaxy sample is essentially defined by five parameters: absorption redshift, z_{abs} , Mg II $\lambda 2796$ rest equivalent width, $W_0^{\lambda 2796}$, H I column density, $\log N_{HI}$, galaxy impact parameter, b , and galaxy luminosity, which we express as a fraction of L^* , L/L^* . The three galaxy identifications from Table 15 that have measured b values but no L/L^* measurements are not included. The sample we analyse includes 80 absorption systems and their identified galaxies. Figure 19 shows the distributions of these properties at a glance. Open circles are systems with $\log N_{HI} < 20.3$ and solid circles are DLAs. In Table 16, we provide results from the Spearman rank correlation test in order to quantify possible correlations among the various parameters⁶. Column 1 gives the pair of parameters between which the correlation test was performed, and column 2 is the Spearman rank coefficient, r_S . A value of $r_S = 0$ indicates no correlation, while $r_S = \pm 1$ indicate a perfect correlation and a perfect anticorrelation, respectively. Column 3 gives P_S , the significance of the deviation of r_S from 0. A small value of P_S indicates significant correlation (positive r_S) or anticorrelation (negative r_S). Column 4 gives the number of standard deviations that the given correlation deviates from the null hypothesis.

In addition, Table 17 lists KS test probabilities that two given samples are drawn from the same parent population.

⁶ Note that while statistical correlations are derived using L/L^* values, we plot $\log L/L^*$ in figures for clarity.

Table 15. Absorbing Galaxy Identifications (*This work*)

Quasar	z_{em}	z_{abs}	$W_0^{\lambda 2796}$ (Å)	$\log N_{HI}$ (cm ⁻²)	Obj. #	Impact parameter		$z_{phot} \pm \sigma$	m_{AB}^a	L/L^*	ID Method	CL
0021+0043	1.245	0.5203	0.533	19.54	1	10.8	67.3	0.549 ± 0.070	19.25	0.73	Photoz	1
...	...	0.9420	1.777	19.38	2	10.8	85.2	...	20.11	1.26	Colour	2
0041-266	3.053	0.8626	0.67	<18.00	1	11.6	89.2	...	...^b	...	Prox	3
0107-0019	0.738	0.5260	0.784	18.48	1	2.6	16.3	0.564 ± 0.157	20.11	0.31	Photoz	1
0116-0043	1.282	0.9127	1.379	19.95	1	8.1	63.4	0.717 ± 0.248	20.71	0.66	Photoz	1
0123-0058	1.551	0.8686	0.757	<18.62	1	1.3	10.0	...	21.1:	0.41	Prox	3
0138-0005	1.340	0.7821	1.208	19.81	2	6.5	48.4	...	22.34	0.11	Prox	3
0139-0023	1.384	0.6828	1.243	20.60	2	5.7	40.3	0.661 ± 0.075	21.60	0.14	Photoz	1
0141+339	1.450	0.4709	0.78	18.88	1	5.3	31.3	...	20.79	0.14	Prox	3
0152+0023	0.589	0.4818	1.340	19.78	2	5.3	31.7	0.518 ± 0.110	21.45(<i>H</i>)	0.10	Photoz	1
0153+0009	0.837	0.7714	2.960	19.70	1	4.9	36.3	0.745 ± 0.040	21.01	0.33	Photoz	1
0253+0107	1.035	0.6317	2.571	20.78	1	1.2	8.2	0.632 ^c	21.5:	0.14	Photoz	2
0254-334	1.849	0.2125	2.23	19.41	1	5.5	19.0	0.030 ± 0.220	22.86	0.005	Photoz	2
0256+0110	1.349	0.7254	3.104	20.70	1	2.4	17.4	0.815 ± 0.080	19.55	1.17	Photoz	2
0710+119	0.768	0.4629	0.62	<18.30	...	...	...	...	...	...	...	...
0735+178	>0.424	0.4240	1.32	<19.00	4	12.7	70.7	0.423 ± 0.179	19.98	0.22	Photoz	1
0843+136	1.877	0.6064	0.938 ^d	19.56	8	10.1	68.0	0.443 ± 0.281	22.46	0.05	Photoz	2
0953-0038	1.383	0.6381	1.668	19.90	1	11.9	81.8	0.644 ± 0.150	19.78	0.71	Photoz	1
0957+003	0.907	0.6720	1.936 ^d	19.59	...	...	...	...	...	...	...	...
1009+0036	1.699	0.9714	1.093	20.00	1	2.5	19.9	...	...^b	...	Prox	3
1009-0026	1.244	0.8426	0.713	20.20	2	5.2	39.7	...	21.68	0.23	Prox	3
...	...	0.8866	1.900	19.48	...	...	...	...	...	...	...	...
1019+309	1.319	0.3461	0.70	18.18	3	9.2	45.1	0.244 ± 0.167	21.81	0.03	Photoz	2
1028-0100	1.531	0.6322	1.579	19.95	...	...	...	...	...	...	...	...
...	...	0.7087	1.210	20.04	...	...	...	...	...	...	...	...
1047-0047	0.740	0.5727	1.063	19.36	1	4.7	30.7	...	21.10	0.17	Prox	2
1048+0032	1.649	0.7203	1.878	18.78	3	7.4	53.5	0.947 ± 0.300	20.54	0.46	Photoz	1
1107+0048	1.392	0.7404	2.952	21.00	2	7.9	57.7	...	23.83(<i>r</i>)	0.17	Colour	3
1109+0051	0.957	0.4181	1.361	19.08	1	1.3	7.2	...	22.24(<i>J</i>)	0.05	Prox	2
...	...	0.5520	1.417	19.60	3	10.0	64.2	0.645 ± 0.157	22.88	0.03	Photoz	2
1209+107	2.193	0.6295	2.619 ^d	20.30	1	1.7	11.6	0.644 ± 0.100	19.89	0.55	Photoz	1
1225+0035	1.226	0.7730	1.744	21.38	1	8.2	60.8	...	...^b	...	Prox	2
1226+105	2.305	0.9376	1.646 ^d	19.41	1	4.6	36.2	0.947 ± 0.060	20.44	0.77	Photoz	1
1323-0021	1.390	0.7160	2.229	20.54	1	1.4	10.1	...	21.90(<i>r</i>)	0.97	Prox	2
1342-0035	0.787	0.5380	2.256	19.78	...	...	...	...	...	...	...	...
1345-0023	1.095	0.6057	1.177	18.85	2	7.6	51.0	0.628 ± 0.040	22.24	0.06	Photoz	1
1354+258	2.006	0.8585	1.176 ^d	18.57	2	4.0	30.7	...	23.78(<i>R</i>)	0.48	Prox	3
...	...	0.8856	0.489 ^d	18.76	3	12.2	94.6	...	23.68(<i>R</i>)	0.49	Prox	3
1419-0036	0.969	0.6238	0.597	19.04	3	9.6	65.3	0.499 ± 0.177^e	22.89(<i>r'</i>)	0.17	Photoz	2
...	...	0.8206	1.145	18.78	...	...	...	...	...	...	...	...
1426+0051	1.333	0.7352	0.857	18.85	1	5.0	36.4	...	22.96(<i>r'</i>)	0.44	Prox	2
...	...	0.8424	2.618	19.65	...	...	...	...	...	...	...	...
1431-0050	1.190	0.6085	1.886	19.18	1	2.6	17.5	0.737 ± 0.224	21.2:	0.17	Photoz	2
...	...	0.6868	0.613	18.40	2	3.3	23.4	...	23.2(<i>r</i>)	0.28	Colour	2
1436-0051	1.275	0.7377	1.142	20.08	...	...	...	...	...	...	...	...
...	...	0.9281	1.174	<18.82	...	...	...	...	...	...	...	...
1437+624	1.090	0.8723	0.71	<18.00	2	9.5	73.3	0.694 ± 0.190	20.70	0.60	Photoz	1
1521-0009	1.318	0.9590	1.848	19.40	1	8.5	67.4	...	23.46(<i>J</i>)	0.10	Colour	2
1525+0026	0.801	0.5674	1.852	19.78	1	4.8	31.3	...	19.59	0.66	Prox	3
1704+608	0.371	0.2220	0.562 ^f	18.23	2	7.7	27.5	0.220 ± 0.050	19.63	0.08	Photoz	1
1714+5757	1.252	0.7481	1.099	19.23	1	2.4	17.6	...	24.33(<i>r</i>)	0.13	Prox	3
1715+5747	0.697	0.5579	1.001	19.18	...	...	...	...	...	...	...	...
1716+5654	0.937	0.5301	1.822	19.98	1	1.1	6.9	0.5301 ^c	23.44(<i>r</i>)	0.07	Photoz	2
1722+5442	1.215	0.6338	1.535	19.00	2	6.6	45.2	...	24.10(<i>r'</i>)	0.09	Colour	3
1727+5302	1.444	0.9448	2.832	21.16	1	3.1	24.5	0.9448 ^c	23.14	0.08	Photoz	2
...	...	1.0312	0.922	21.41	2	3.6	29.0	...	20.94	0.71	Prox	2
1729+5758	1.342	0.5541	1.836	18.60	2	5.6	36.0	0.503 ± 0.140	20.56	0.26	Photoz	1
1733+5533	1.072	0.9981	2.173	20.70	1	8.4	67.2	...	24.4(<i>g</i>)	0.47	Colour	2
1857+566	1.578	0.7151	0.65	18.56	...	...	...	...	...	...	...	...
2149+212	1.538	0.9114	0.72	20.70	1	1.7	13.3	...	22.31(<i>I</i>)	0.31	Prox	2
...	...	1.0023	2.46	19.30	3	5.5	44.0	...	22.37(<i>I</i>)	0.41	Prox	3

Table 15. Continued

Quasar	z_{em}	z_{abs}	$W_0^{\lambda 2796}$ (Å)	$\log N_{HI}$ (cm^{-2})	Obj. #	Impact parameter		$z_{phot} \pm \sigma$	m_{AB}^a	L/L^*	ID Method	CL
2212–299	2.706	0.6329	1.15 ^f	19.75	1	2.3	16.0	...	20.90	0.25	Colour	2
2223–052	1.404	0.8472	0.586 ^f	18.48	1	6.9	52.8	...	24.62(<i>B</i>)	0.32	Prox	2
2328+0022	1.308	0.6519	1.896	20.32	1	1.7	11.8	0.815 ± 0.242	22.61(<i>r'</i>) ^g	0.33	Photoz	1
2334+0052	1.040	0.4713	1.226	20.65	1	5.5	32.5	0.4713 ^c	20.37	0.20	Photoz	2
2353–0028	0.765	0.6044	1.601	21.54	1	4.9	32.9	0.844 ± 0.300	19.27	1.01	Photoz	1

^a Apparent *K* magnitudes are provided, unless otherwise noted. The symbol “:” indicates that the magnitude is uncertain because the galaxy overlaps with the quasar PSF.

^b Observations not photometric.

^c “BestTemplate” fit calculated by fixing the redshift of the stellar population template at the absorption redshift, to illustrate that a galaxy template consistent with the measured photometry exists.

^d Measurements of $W_0^{\lambda 2796}$ have been changed from RTN06 values to reflect the more recent measurements of Quider et al. (2011).

^e SDSS photometric redshift, *AB*-converted SDSS magnitudes are provided.

^f Measurements of $W_0^{\lambda 2796}$ have been changed from RTN06 values to reflect the more recent measurements of Mathes et al. (in preparation).

^g SDSS magnitudes provided by S. Zibetti (private communication).

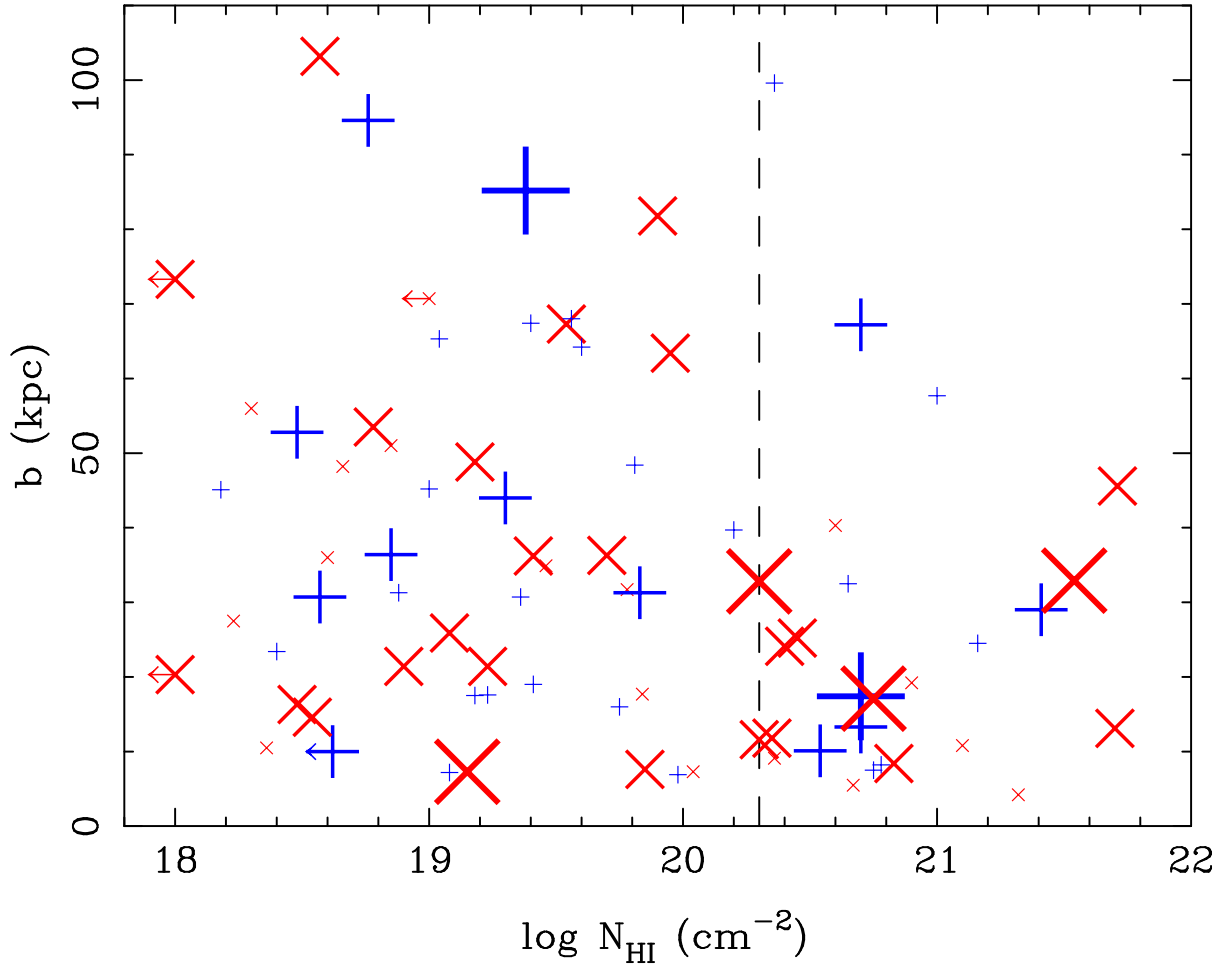


Figure 18. Impact parameter, b , versus $\log N_{HI}$. Galaxy luminosity is represented by the size of the symbol. The smallest symbols are galaxies with $L \leq 0.3L^*$, the medium-sized symbols, $0.3L^* < L \leq L^*$, and the largest symbols represent $L > L^*$. Red crosses represent galaxies with identification confidence level CL = 1, and blue ‘+’ symbols are those that have CL = 2 or 3. The dashed line is at the DLA threshold column density of $\log N_{HI} = 20.3$.

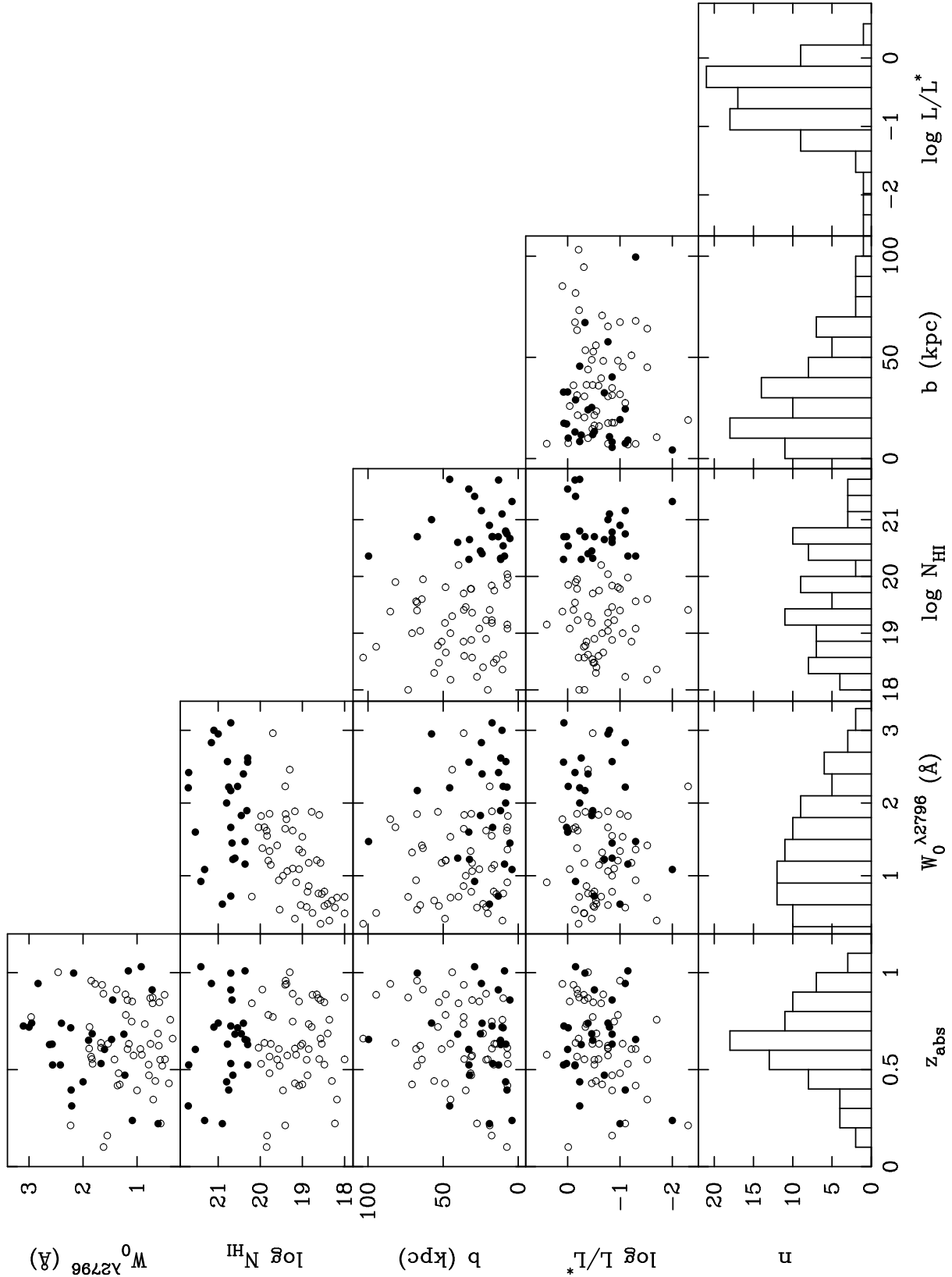


Figure 19. Absorber properties at a glance. Filled circles are DLAs and open circles are systems with $\log N_{\text{HI}} > 20.3$. For clarity, the upper limit arrows for column density are not shown. See Tables 14 and 15 for the four systems with upper limits for $\log N_{\text{HI}}$, but with measured values for b and L .

Table 17. KS Test Probabilities, P_{KS} , for Various Pairs of Sub-samples

Parameter	DLA vs. SubDLA ^a	SubDLA vs. LLS ^a
z_{abs}	0.595	0.624
$W_0^{\lambda 2796}$	0.003	0.0003
b	0.089	0.828
L/L^*	0.976	0.087
$W_0^{\lambda 2796} \leq 1.35 \text{ \AA}$ vs. $W_0^{\lambda 2796} > 1.35 \text{ \AA}$ ^b		
z_{abs}	0.893	
b	0.361	
$\log N_{HI}$	0.0001	
L/L^*	0.139	
$b \leq 30.7 \text{ kpc}$ vs. $b > 30.7 \text{ kpc}$ ^c		
z_{abs}	0.724	
$W_0^{\lambda 2796}$	0.531	
$\log N_{HI}$	0.043	
L/L^*	0.983	

^aThe DLA sample: $\log N_{HI} \geq 20.3$; the SubDLA sample: $19.0 < \log N_{HI} < 20.3$; the LLS sample: $\log N_{HI} \leq 19.0$

^bThe median rest equivalent width for the sample of 80 systems with identified galaxies is $W_0^{\lambda 2796} = 1.35 \text{ \AA}$.

^cThe median impact parameter for the sample of 80 identified galaxies is $b = 30.7 \text{ kpc}$.

In the first set, z_{abs} , $W_0^{\lambda 2796}$, b in kpc, and L/L^* are compared for three different samples of H I column density: the DLA ($\log N_{HI} \geq 20.3$) and subDLA ($19 < \log N_{HI} < 20.3$) samples, and for the subDLA and Lyman limit system (LLS, $\log N_{HI} \leq 19$) samples. There are 27 galaxies in the DLA sample, 30 in the subDLA sample, and 23 in the LLS sample. Next, the sample is split by the median value of $W_0^{\lambda 2796}$, and then by the median value of b .

We now discuss these correlations in some detail. The two most significant correlations are between $\log N_{HI}$ and $W_0^{\lambda 2796}$, and between $\log N_{HI}$ and b .

4.3 Trends with Redshift

The first column in Figure 19 shows the redshift distributions of the four primary properties of the sample of 80 galaxies: $W_0^{\lambda 2796}$, $\log N_{HI}$, b , and L/L^* . Table 16 shows that the strongest correlations, albeit less than 2σ , are between z_{abs} , and L/L^* and b . The luminosity - redshift correlation arises from the fact that the two faintest galaxies, those with $\log L/L^* \leq -2$, are among the lowest redshift identifications ($z < 0.3$). The two galaxies are the $z_{abs} = 0.2125$ absorber towards 0254–334 with galaxy luminosity $L = 0.005L^*$ and the $z_{abs} = 0.2377$ absorber towards 0952+179 with galaxy luminosity $L = 0.01L^*$. A point of concern might be that these faint galaxies were detected only because of their low redshifts, and that similarly faint galaxies at higher redshifts, that are the true absorbers, are not being detected.

⁷ The $W_0^{\lambda 2796}$ median value applies to our observed sample and not to the true median of the $W_0^{\lambda 2796}$ distribution over some minimum and maximum $W_0^{\lambda 2796}$ range.

However, Figure 2 showed that the 3σ detection threshold is as faint as $\sim 0.02L^*$ for galaxies (assuming a size of 10 kpc) in a few fields between redshifts 0.2 and 1. While there is always the concern that imaging studies miss very faint galaxies, we do not believe that we are severely limited by this bias in comparison to other studies. In fact, our images go deeper than most other similar studies, and most of the galaxies fainter than $0.1L^*$ have been identified in this study. To illustrate this, Figure 20 shows the luminosity distribution of galaxies with redshift. The black data points are from our groundbased data, and the red data points are galaxies identified in other studies. A KS test shows that the two distributions are similar, with $P_{KS} = 0.873$.

The b versus z_{abs} panel in Figure 19 suggests that there is an upper envelope to the impact parameter distribution that is a function of redshift. At the lowest redshifts ($z_{abs} \lesssim 0.3$), there are no absorbing galaxies at $b \gtrsim 30 \text{ kpc}$. We do not believe that this is due to a bias, because we are unaware of low-redshift systems with unidentified absorbing galaxies. For example, such a bias may have arisen if large impact parameter galaxies were overlooked assuming that such galaxies couldn't be the true absorbers. If this correlation is real, one speculation is that by $z \sim 0.3$, mergers have resulted in fewer clumps of gas at large distances from the centers of galaxies. Also see Section 4.10.

Of course, the trends here are weak: the Spearman rank test results in only a 1.6σ correlation between b and z_{abs} (Table 16), and the KS test between z_{abs} samples split by median b (30.7 kpc) shows that the two distributions are similar ($P_{KS} = 0.724$, Table 17).

Table 17 also shows that the redshift distributions of samples split by $\log N_{HI}$ or by $W_0^{\lambda 2796}$ are statistically similar.

4.4 Dependence of $\log N_{HI}$, b , and L/L^* on $W_0^{\lambda 2796}$

The most significant correlation, one that has previously been recognized (RTN06), is seen between $W_0^{\lambda 2796}$ and $\log N_{HI}$, with $r_S = 0.53$, $P(r_S) = 5.1 \times 10^{-7}$, and $N_\sigma = 4.7$ (Table 16)⁸. The H I column density clearly depends on $W_0^{\lambda 2796}$, although the relation is not tight (see Figure 19, and Figures 2 and 3 of RTN06), i.e., one cannot predict the value of $\log N_{HI}$ given $W_0^{\lambda 2796}$. As discussed in RTN06, the fraction of MgII systems that are DLAs increases with $W_0^{\lambda 2796}$, and there are no DLAs with $W_0^{\lambda 2796} < 0.6 \text{ \AA}$. Since this imaging sample is largely derived from the RTN06 MgII sample (72 of the 80 systems are from RTN06), the same trend is seen here.

It is clear from Table 17 that the $W_0^{\lambda 2796}$ distributions of the DLA, subDLA, and LLS samples are very significantly different. They differ at the 99.7% (or 3σ) confidence level for the DLAs and subDLAs, and at the 99.97% (4σ) confidence level for the subDLA and LLS samples. This is also seen in the KS test probability for the two N_{HI} samples divided by the median value of $W_0^{\lambda 2796}$ ($P_{KS} = 0.0001$). The trends are

⁸ For the RTN06 sample, which included 195 MgII systems with $0.1 < z_{abs} < 1.65$, the $W_0^{\lambda 2796}$ versus $\log N_{HI}$ correlation is significant at the 8.4σ level. For the 123 systems with $z_{abs} < 1$, we find the relation to be significant at the 6.1σ level. The current imaging sample contains 80 systems with $z < 1$.

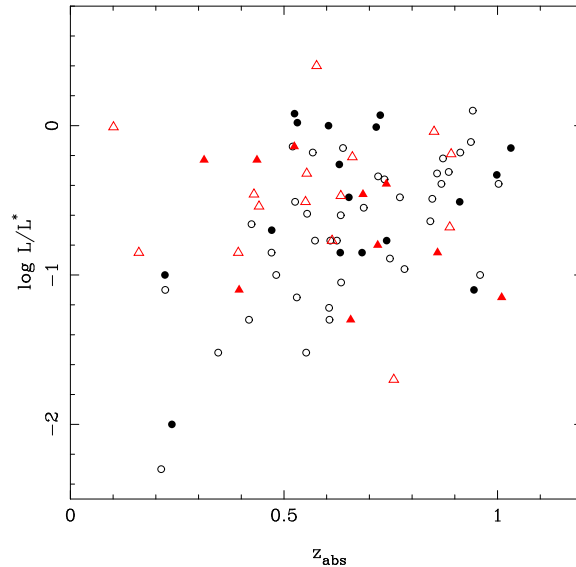


Figure 20. Galaxy luminosity vs. absorption redshift. The black circles are galaxies that we have identified using our groundbased data. Solid circles represent DLAs and open circles are systems with $\log N_{\text{HI}} < 20.3$. The red triangles are galaxy identifications from other work (see Table 14). Solid triangles are DLAs and open triangles are systems with $\log N_{\text{HI}} < 20.3$.

better visualized in the “box and whisker” plots of Figure 21. The crosses are the minimum, median, and maximum values, and the bottom and top edges of the box are the first and third quartile values of each subsample. The median values of $W_0^{\lambda 2796}$, which are 2.0 Å for the DLA sample, 1.37 Å for the subDLA sample, and 0.78 Å for the LLS sample, do show a very significant trend with $\log N_{\text{HI}}$. (See also Ménard & Chelouche 2009, who fit a power-law to the median values of N_{HI} from RTN06 as a function of $W_0^{\lambda 2796}$.)

Table 16 shows that b and L/L^* do not correlate significantly with $W_0^{\lambda 2796}$. The $W_0^{\lambda 2796}$ versus b correlation is more significant, with $N_\sigma = 1.8$. Moreover, the correlation coefficient is negative reflecting the fact that there are no large $W_0^{\lambda 2796}$, large b absorbers. The $W_0^{\lambda 2796}$ versus L/L^* correlation is significant only at the 0.8σ level. Figure 19 shows that if the two lowest luminosity galaxies are ignored, the $W_0^{\lambda 2796}$ versus L/L^* distribution is essentially uniform with the vast majority of galaxies having luminosities between 0.1 and $1L^*$. We note here that Chen et al. (2010) fit a power-law model to $W_0^{\lambda 2796}$ as a function of a luminosity-scaled impact parameter. Their sample includes $W_0^{\lambda 2796}$ measurements as low as 0.1 Å and upper limits as low as 0.02 Å, from which they derive a statistically significant anti-correlation between $W_0^{\lambda 2796}$ and the luminosity-scaled b . However, in agreement with our results, their data show no trend for $W_0^{\lambda 2796} \geq 0.3$ Å, which is the lower limit of our sample.

Splitting the sample by the median value of $W_0^{\lambda 2796}$ results in KS test probabilities for the four other parameters as shown in the second section of Table 17. Statistically, the two z_{abs} , b , and L/L^* samples are drawn from the same parent population. The median luminosity is 0.26 L^* for the $W_0^{\lambda 2796} < 1.35$ Å sample and 0.38 L^* for the $W_0^{\lambda 2796} > 1.35$ Å sample. The two N_{HI} samples clearly separate out, with $P_{\text{KS}} = 0.0001$.

To investigate whether brighter galaxies cause stronger Mg II absorption lines than do fainter ones at the same impact parameter, we plot box and whisker diagrams of

$\log L/L^*$ versus $W_0^{\lambda 2796}$ for four b samples. Figure 22 shows the range of $\log L/L^*$ values for samples split by the median value of $W_0^{\lambda 2796}$ as a function of b . Each of the four b samples, labeled along the x-axis in kpc, has 20 systems, and each $W_0^{\lambda 2796}$ subsample has 10 systems. The median value of $W_0^{\lambda 2796}$ for each b sample is indicated in units of Å at the top of each panel. It is interesting, and perhaps unexpected, that except perhaps in the third impact parameter bin, galaxy luminosity and Mg II rest equivalent width are not correlated.

4.5 Dependence of b and L/L^* on $\log N_{\text{HI}}$

The third column of Figure 19 shows the b and L/L^* distributions as a function of $\log N_{\text{HI}}$. Statistically, we see a strong, 3.0σ , correlation between $\log N_{\text{HI}}$ and b (Table 16), and no significant correlation between $\log N_{\text{HI}}$ and L/L^* . The third section of Table 17 also shows that, except for the $\log N_{\text{HI}}$ subsamples, the z_{abs} , $W_0^{\lambda 2796}$, and L/L^* subsamples are statistically similar when split by the median impact parameter of the sample, $b = 30.7$ kpc.

Figure 23 shows the normalized cumulative distributions of b and $\log L/L^*$ for three samples of H I column density. The solid circles with red lines are b and $\log L/L^*$ values for DLA galaxies, the open circles with blue lines represent subDLA galaxies, and the open triangles with orange lines represent LLS galaxies. The impact parameter distributions for the subDLA and LLS galaxies are very similar with KS test probability $P_{\text{KS}} = 0.828$ (Table 17). On the other hand the DLA galaxy b distribution is markedly different, with KS test probability $P_{\text{KS}} = 0.022$ that the DLA and $\log N_{\text{HI}} < 20.3 \text{ cm}^{-2}$ (subDLA plus LLS) sample’s galaxy impact parameters are drawn from the same population, i.e., the null hypothesis is rejected at the 97.8% confidence level, or better than 2σ . Individually for the two non-DLA samples, we find $P_{\text{KS}}(\text{DLA}, \text{subDLA}) = 0.089$ and $P_{\text{KS}}(\text{DLA}, \text{LLS}) = 0.030$. The two $\log N_{\text{HI}}$ subsam-

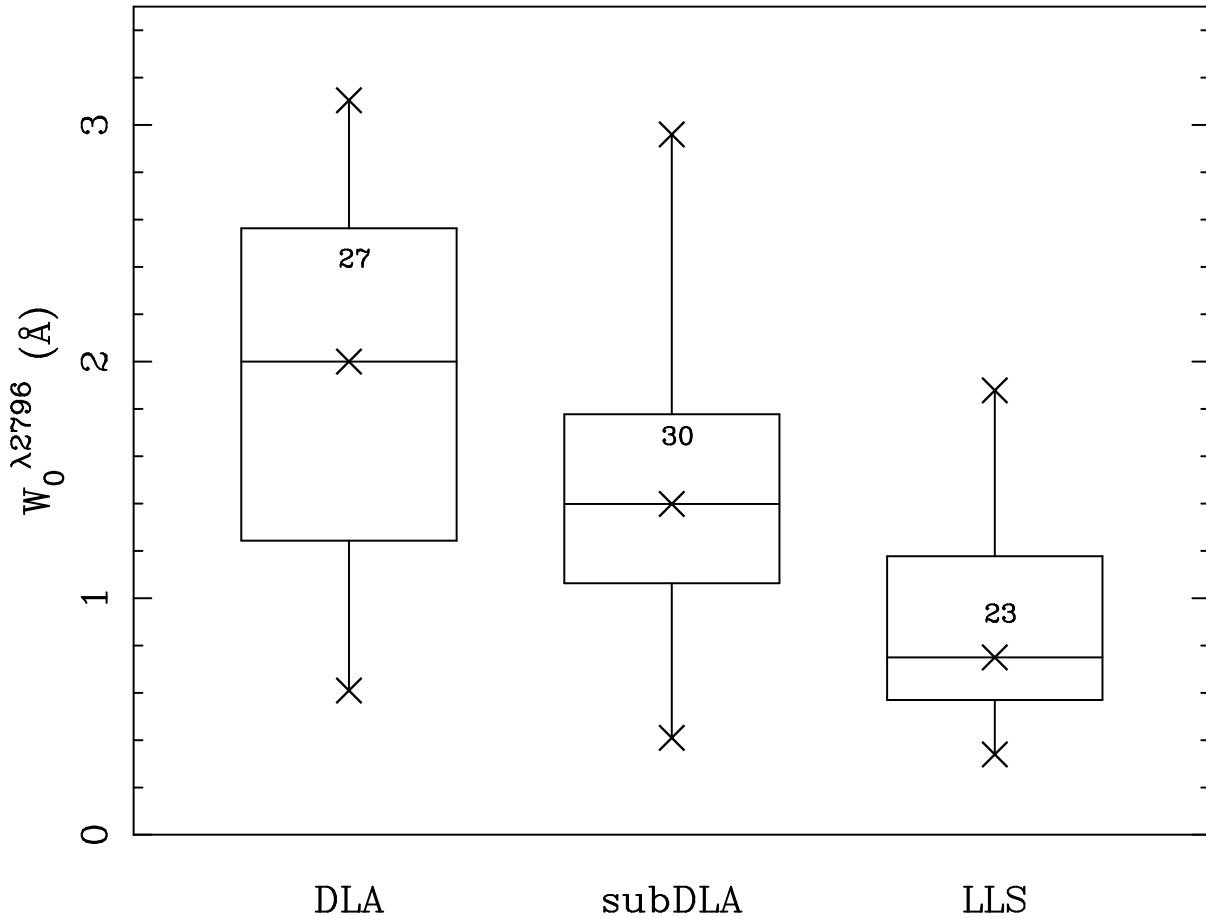


Figure 21. A “box and whisker” plot showing the distribution of Mg II $\lambda 2796$ rest equivalent widths for the indicated N_{HI} subsamples. The DLA subsample includes systems with $\log N_{HI} \geq 20.3$, the subDLA sample has $19.0 < \log N_{HI} < 20.3$, and the LLS sample has $\log N_{HI} \leq 19.0$. The three crosses in each box and whisker plot indicate the minimum, median, and maximum of the distribution. The bottom and top of the box are the 25th and 75th percentile (the lower and upper quartile of the distribution) respectively. The numbers in each box indicate the number of systems in each subsample.

ples split by median b are also statistically different at the $\sim 2\sigma$ level with $P_{KS} = 0.043$ (Table 17).

Figure 23 shows that the median values of the DLA and subDLA b distributions are very different. In order to quantify the dispersion in the data, we use the “median absolute deviation (MAD),” which is defined as the median of the absolute deviations from the data’s median for the sample under consideration. It gives an estimate of the spread in values about the median, and is a statistic that is not sensitive to extreme outliers in the data. We find that the median impact parameter for the DLA sample is $b = 17.4$ kpc (with $b_{MAD} = 9.0$ kpc), while the median value for the subDLA sample is $b = 33.3$ kpc (with $b_{MAD} = 15.8$ kpc), or twice as large. For the LLS sample, the median is $b = 36.4$ kpc (with $b_{MAD} = 16.1$ kpc). The impact parameter distributions are shown graphically in the box and whisker diagrams of Figure 24. As before, the crosses are the minimum, median, and maximum values, and the bottom and top edges of the box are the first and third quartile values of the sample. While there is overlap in the impact parameter distributions of DLA and subDLA systems, both the cumulative (Figure 23) and the box and whisker plots (Figure 24) show that

they are clearly different⁹. The subDLA (and LLS) galaxies tend to be farther away from the quasar sightline.

In Figure 25, we plot the median value of $\log N_{HI}$ as a function of b , with the binning chosen to include an equal number of systems in each bin. The horizontal bars indicate bin size, and the vertical bars are the first and third quartile of the range of $\log N_{HI}$ values in each bin. Thus, outliers are not represented in this plot. The red curve is an exponential fit to the median values alone, and does not include errors. It has an e -folding length of 12 kpc, which occurs at $\log N_{HI} \approx 20.0$. While there is a large spread in H I column densities at any given impact parameter, this plot illustrates that the median value of $\log N_{HI}$ declines roughly exponentially with impact parameter.

On the other hand, the galaxy luminosity distributions for the three N_{HI} samples are more similar (Table 17). The KS test probability is $P_{KS} = 0.976$ for the DLA and subDLA

⁹ In fact, the maximum value of the DLA b distribution is 99.6 kpc. The identification of this galaxy is controversial (see §6). The next highest value is $b = 67.2$ kpc (see Figure 23 for example). So if the $b = 99.6$ kpc value is ignored, there is less of an overlap in the b values of the two samples.

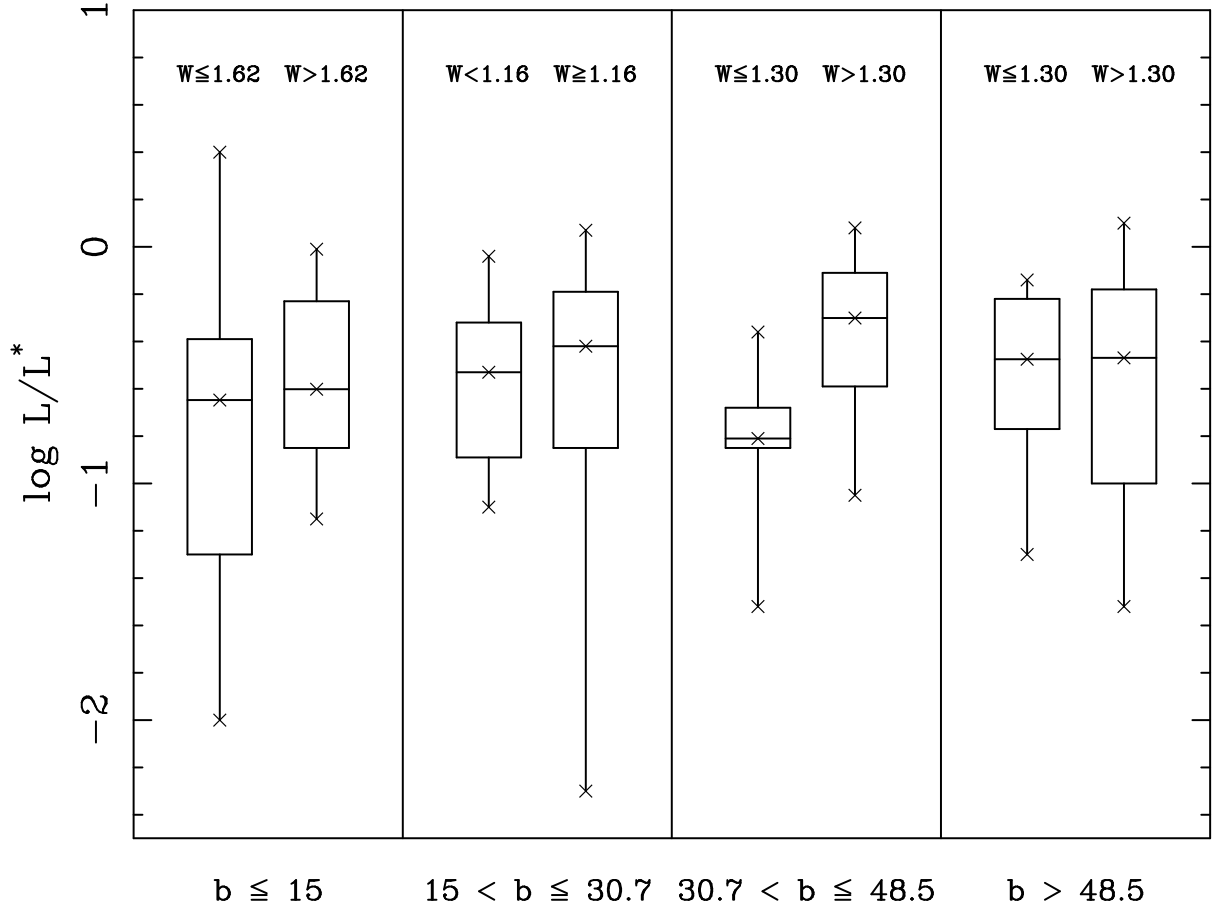


Figure 22. Box and whisker diagram showing galaxy luminosity distributions as a function of $W_0^{\lambda 2796}$ for four bins of impact parameter. Each of the four b samples, labeled along the x-axis in kpc, has 20 systems, and each $W_0^{\lambda 2796}$ subsample has 10 systems. The median value of $W_0^{\lambda 2796}$ for each impact parameter is indicated in units of \AA at the top of each panel.

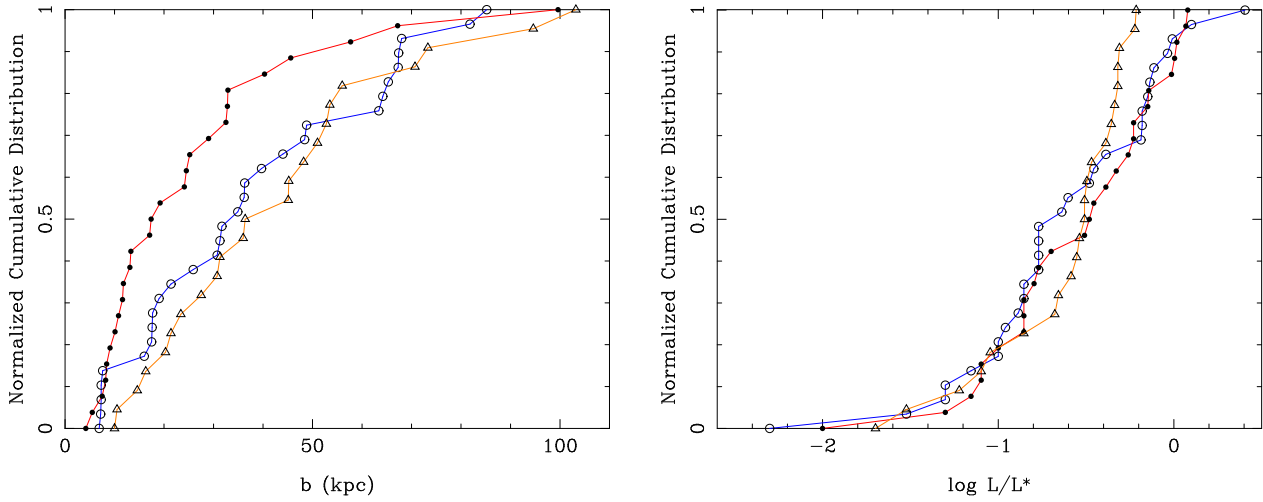


Figure 23. Normalized cumulative distributions of impact parameter, b , in the left panel, and luminosity, $\log L/L^*$, in the right panel. Red solid circles are DLAs, blue open circles are subDLAs, and orange open triangles are LLSs.

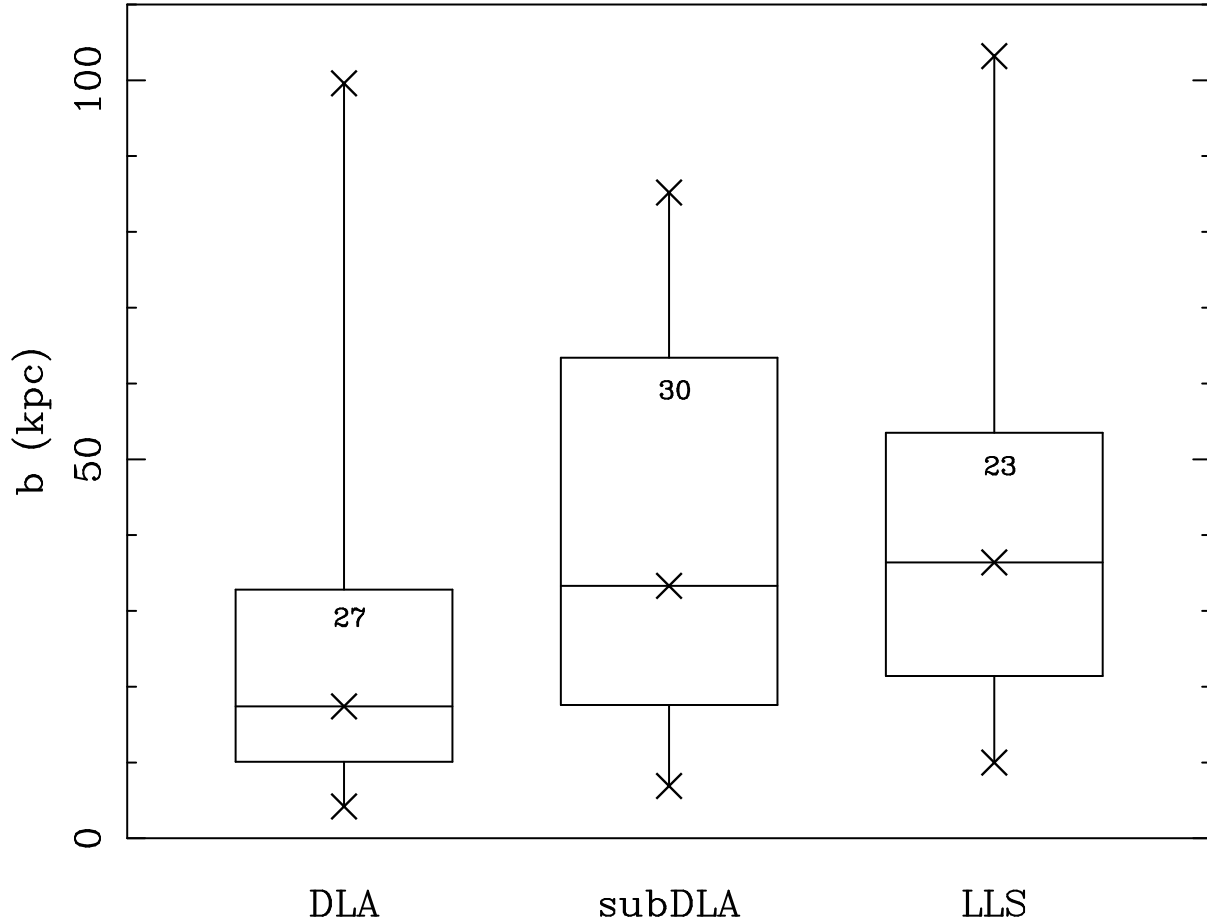


Figure 24. Same as in Figure 21, but for the impact parameter distribution of the sample.

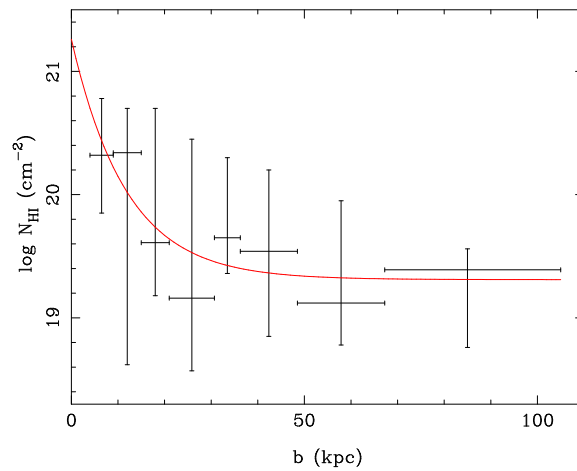


Figure 25. Median values of $\log N_{HI}$ are plotted as a function of b . The horizontal bars are bin sizes chosen to include an equal number of systems in each bin. The vertical bars indicate lower and upper quartiles of $\log N_{HI}$ values in each bin. Outliers are not included in this plot. The red curve is an exponential fit to the median values, and has an e -folding length of 12 kpc. Errors are not included in the fit.

samples, 0.087 for the LLS and subDLA samples, and 0.228 for the DLA and LLS samples (not tabulated). The latter two are not considered to be statistically significant. It can also be seen from Figure 23 that the median values of the three luminosity distributions are very similar ($0.33L^*$,

$0.20L^*$, and $0.31L^*$ for the DLA, subDLA, and LLS samples, respectively).

Despite the fact that we have assembled the largest sample of DLA and subDLA galaxies thus far, small number statistics still play a relatively significant role. Consider for

example, the case of the galaxy identified as the $z = 0.313$ absorber in the 1127–145 field. In Rao et al. (2003) we identified a dwarf galaxy, which is perhaps associated with several brighter galaxies at the same redshift, as the absorber because of its proximity to the quasar sightline. Its luminosity is $0.01L^*$, and it is at a projected distance of $b = 16.1$ kpc from the quasar sightline. However, more recently, Kacprzak et al. (2010) have shown that the kinematics of the Mg II absorbing gas are more consistent with the gas being associated with the more luminous $0.59L^*$ galaxy that is 45.6 kpc from the quasar sightline. We have adopted this new interpretation (see Table 14) for this absorber. We believe that the identification is still debatable since no spectroscopic redshift exists for the dwarf galaxy. Kacprzak et al. (2010) speculate that it might be near the quasar redshift. Nevertheless, had we retained our original identification for this system, the b and L distributions would change slightly: the DLA and subDLA impact parameter distributions would then be inconsistent with each other at the 96% confidence level ($P_{KS} = 0.041$). The DLA and subDLA luminosity distributions would be nearly identical, with KS test probability $P = 0.9999$.

We now investigate whether brighter galaxies have larger impact parameters within each N_{HI} sample. We have already seen that brighter galaxies at the same impact parameter do not give rise to higher values of $W_0^{\lambda 2796}$ (§4.4), and so we do not expect any trends here. The data are shown pictorially in Figure 26 as box and whisker plots. There is significant overlap within all three N_{HI} subsamples, and there is no evidence that galaxies that are farther away (larger b) are more luminous.

4.6 Luminosity versus Impact Parameter

This correlation is significant only at the 1.2σ level (Table 16). The galaxy at $b = 99.6$ kpc is identified with the 1622 + 239 $z_{abs} = 0.6561$ DLA system (see the fourth column of Figure 19). It might seem that without this data point, one would conclude that low luminosity absorber galaxies are not found at high impact parameters. (The identification of this galaxy as the DLA absorber is debatable. See §6.) However, the significance of the correlation improves only to 1.5σ without this system.

4.7 Principal Component Analysis

In order to explore whether absorber galaxy properties occupy any preferred direction in a multi-parameter space, we also performed a principal component analysis (PCA) using the four parameters that characterize the absorber: $W_0^{\lambda 2796}$, $\log N_{HI}$, b , and L/L^* . The PCA did not reveal any useful information. Each of the four eigenvectors included multiple parameters with non-negligible eigencoefficients. In other words, four eigenvectors had to be used to effectively explain the overall variance in the sample. The four eigenvectors are:

$$EV1 = 0.63W + 0.64N - 0.39b + 0.18L$$

$$EV2 = 0.04W - 0.05N + 0.40b + 0.91L$$

$$EV3 = -0.35W - 0.26N - 0.82b + 0.36L$$

$$EV4 = 0.69W - 0.72N - 0.08b - 0.03L$$

with eigenvalues 1.75, 1.00, 0.84, and 0.42 respectively. In these equations we have abbreviated $W_0^{\lambda 2796}$ with W , $\log N_{HI}$ with N , and L/L^* with L .

4.8 Galaxy Types

The stellar population synthesis model fits used to calculate photometric redshifts also provide information on galaxy type. We followed the classification scheme of Budavari et al. (2003), whose templates were also used in this study. Details of our photometric redshift fits are given in the Appendix. Budavari et al. (2003) used a spectral-type parameter that is essentially derived from the rest-frame colours of the best-fit spectral energy distribution (SED). Using this same classification we find that of the 27 galaxies with photometry for which we were able to fit templates, i.e., those for which photometry in four or more filters exists, 4 have SEDs that are consistent with being ellipticals, 8 can be classified as spiral type Sbc, 9 as Scd, and 6 as irregular. Of the 27, eight are DLA galaxies with template fits: one is an elliptical, two are of type Sbc, four are Scd, and one is an irregular galaxy. Similarly, of the 11 subDLA and 8 LLS galaxies with template fits, the distribution is (2,2,5,2) and (1,4,0,3), respectively, for types (E, Sbc, Scd, Irr).

Thus, as has been known from previous studies, we can now confirm with a larger sample that DLA galaxies are predominantly late, star-forming galaxies, but span the entire range of galaxy spectral types. We also find the same result for subDLA and LLS galaxies. Since SED fits were made for a random subset of galaxies in our sample, that depended mainly on observing parameters, we expect the same distribution of types for the remainder of the sample, i.e., for galaxies with insufficient photometry to carry out template fits. Moreover, we also showed that the CL = 1 sample, i.e., the sample for which spectral-types could be determined, has the same properties as the CL = 2 or 3 sample (§4.2).

4.9 Metallicity and Galaxy Properties

Figure 27 shows plots of metallicity measurements, specifically $[Zn/H]$, from the literature as a function of absorption line parameters $W_0^{\lambda 2796}$ and $\log N_{HI}$, and galaxy parameters b and L/L^* . Even with this small sample, it can be seen that higher $W_0^{\lambda 2796}$ systems tend to have higher metallicities (e.g., Nestor et al. 2003, Turnshek et al. 2005, Kulkarni et al. 2010). The tendency for subDLAs to have higher metallicities than DLAs is also apparent (e.g., Meiring et al. 2009). However, no trends with galaxy properties can be deduced from the two panels on the right in Figure 27. One might expect that more luminous, and therefore more massive, galaxies would tend to give rise to higher $W_0^{\lambda 2796}$ systems (since rest equivalent width is an indicator of the velocity spread of the gas), but this is not seen in our sample (see Table 16). One might also expect some of the more luminous galaxies to be more evolved, and thus exhibit higher metallicities, but this is also not seen in our sample. There also does not seem to be any correlation between metallicity and galaxy impact parameter. Of course, the sample is small. More conclusive results must await more measurements of metallicities at $z < 1$.

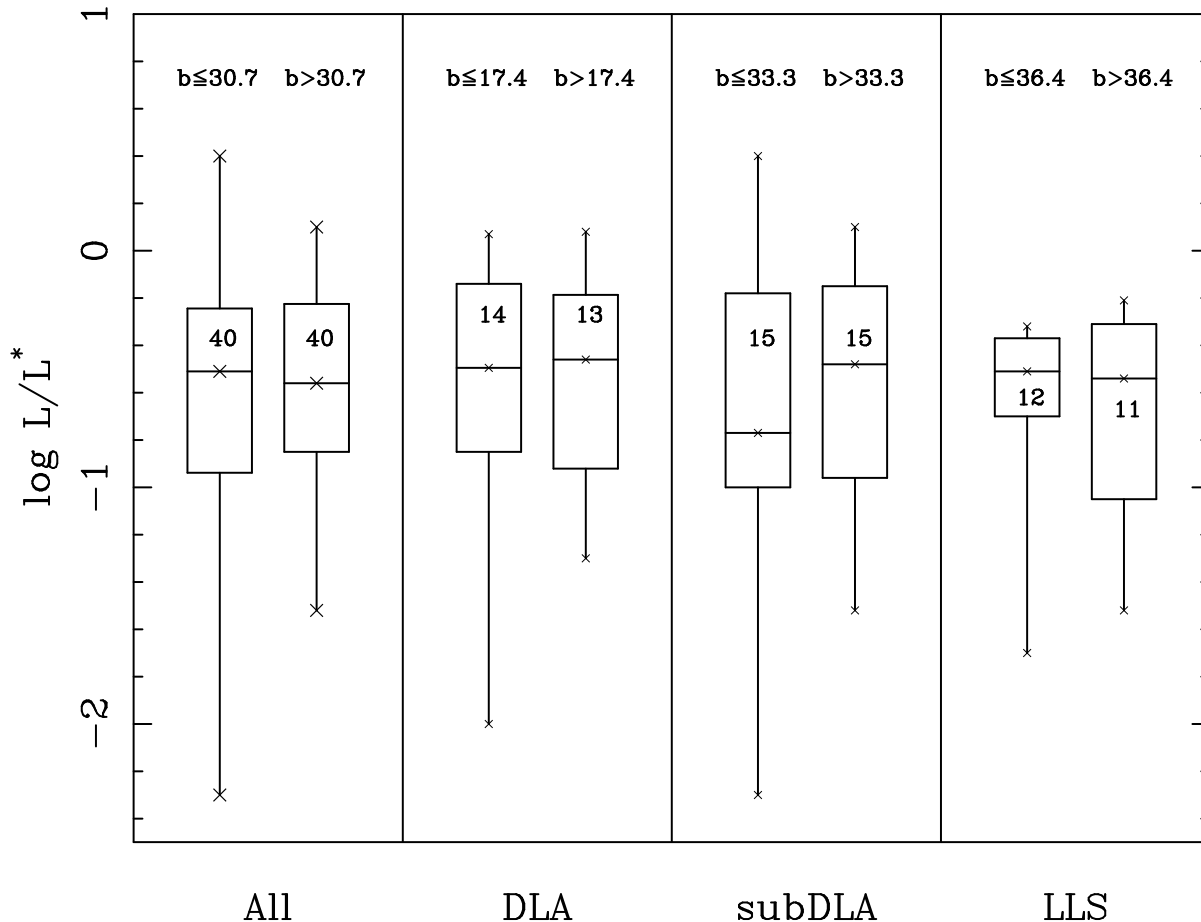


Figure 26. Same as in Figure 21, but for the luminosity distribution of the sample. The full sample is shown in the first panel. The samples have been split by impact parameter and the median impact parameter for each sample, in kpc, is indicated at the top of each panel.

4.10 Comparison with the $z = 0$ Galaxy Distribution

Figure 28 is a plot of b versus $\log N_{\text{HI}}$. Our data for $\log N_{\text{HI}} > 19$ are shown as crosses, with the size of the crosses indicating three different bins in luminosity. The smallest crosses are galaxies with $L < 0.3L^*$, the medium sized crosses are those with $0.3 < L < 1L^*$, and the large crosses represent galaxies with $L > 1L^*$. The subDLAs and the DLAs are separated by the vertical dashed line. The blue solid lines, adapted from Zwaan et al. (2005), approximate the curves drawn in their Figure 15 (their curves only extend to $\log N_{\text{HI}} = 19.5$ at the low H I column density end). They represent the conditional probability of impact parameter as a function of H I column density for local galaxies. Using H I 21-cm line maps of nearby galaxies taken with the Westerbork Synthesis Radio Telescope, they present absorber and galaxy properties in a form that can be used to compare with the properties of higher redshift H I absorbers. Specifically, from their analysis of essentially $z \approx 0$ galaxies, they derive relevant probabilities within this $b - \log N_{\text{HI}}$ plane. The line labeled “median” indicates that there is a 50% probability that the absorber galaxy will lie below this line. The other lines show the 10th, 25th, 75th, 90th, and 99th percentiles for galaxies at $z \approx 0$. Based on the low-redshift DLA galaxy

data available at that time, they concluded that the distributions were similar, although there were somewhat fewer low b systems than expected. Now, with our much larger sample we see that the distributions are markedly different. For $\log N_{\text{HI}} > 19.5$, only eight out of 42 galaxies lie below the median line, and we have no galaxies below the 25th percentile line. As we had discussed in §3, we might have misidentified about four galaxies in our sample due to our inability to probe close to the quasar sightline. Therefore, at most, we would have 4/42, or 9.5% of the sample below the 25th percentile line and 12/42 (28.6%) below the median line. At the high end of the b distribution, we see that 11/42 (26%) of the galaxies are beyond the 99th percentile line. If four of these were the misidentifications 7/42 (17%) would be above this line.

Zwaan et al. (2005) also find that at $z \approx 0$ the most luminous galaxies are most likely to be associated with high N_{HI} DLAs at large impact parameters. The red dotted line in Figure 28 has been adapted from their Figure 18, and indicates that above this line, more than 50% of the galaxies are more luminous than L^* at $z = 0$. We find that out of the 24 galaxies in our sample that have $\log N_{\text{HI}} > 19.5$ and are above this line, only two are more luminous than L^* .

Clearly, the properties of low-redshift DLA and subDLA galaxies differ considerably in comparison to the local pop-

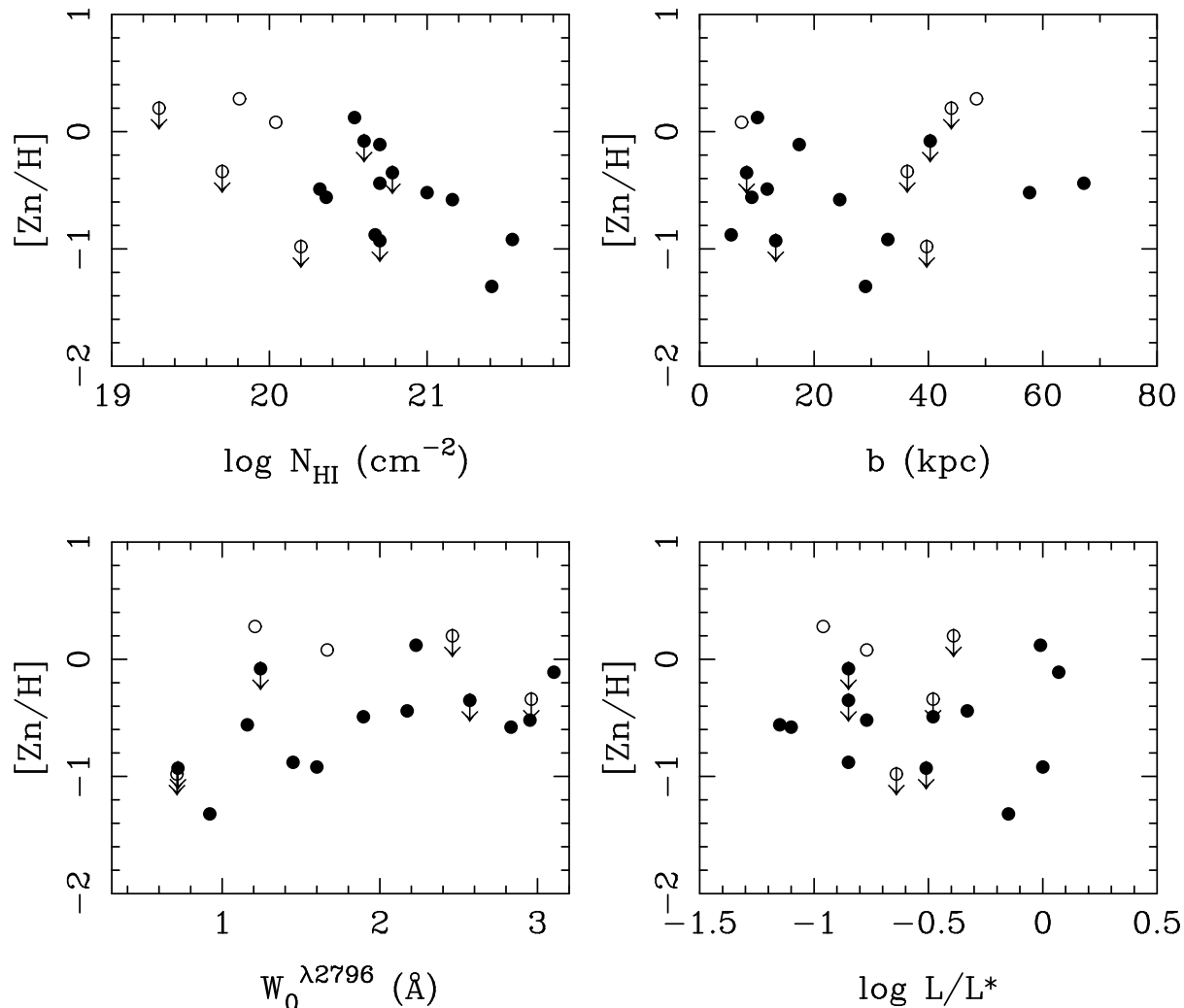


Figure 27. Metallicity measurements from the literature versus absorption line properties $\log N_{HI}$ and $W_0^{\lambda 2796}$ on the left, and galaxy properties b and $\log L/L^*$ on the right.

ulation, and this might be indicative of evolution in the neutral-gas environments of galaxies. Although the statistics at the low redshift end of our sample are small, we find that the impact parameter distribution (Figure 19 and Section 4.3) has an upper envelope that declines between redshifts $z \sim 0.5$ and $z \sim 0$. Taken in combination with the Zwaan et al. results, this is perhaps suggestive of the process of galaxy assembly over the last 5 Gyr. The factor of two decline in Ω_{DLA} over the same redshift interval (RTN06) might also be related to the same phenomenon.

4.11 HST versus Groundbased Identifications

Here we address the question of whether the galaxies identified in HST data have different properties in comparison to galaxies identified in groundbased data. For example, since HST images can probe closer in to the quasar sightline, the impact parameters of galaxies identified in HST images might be systematically smaller.

Of the 29 galaxies that were known prior to this work (Table 14), 17 have been identified in HST images and 12 were first identified in groundbased studies. The 1127–145

absorber was first identified by Bergeron & Boissé (1991) in groundbased data. An HST image of this field was later discussed by Kacprzak et al. (2010). In addition, the 0827+243 field which was in our initial groundbased sample (Rao et al. 2003), was imaged with HST, but the absorber identification remained the same (Steidel et al. 2003). For the purpose of the comparison being made here, these two fields will be considered HST fields.

A KS test gives a probability of $P_{KS} = 0.637$ that the groundbased and HST impact parameter samples are drawn from the same parent population. While it may appear that the HST-identified galaxies have smaller impact parameters (the median b value for the HST identifications is 21.4 kpc versus 31.3 kpc for the groundbased identifications), the distributions of HST and groundbased identifications are statistically similar. Their luminosity distributions are also similar with $P_{KS} = 0.909$.

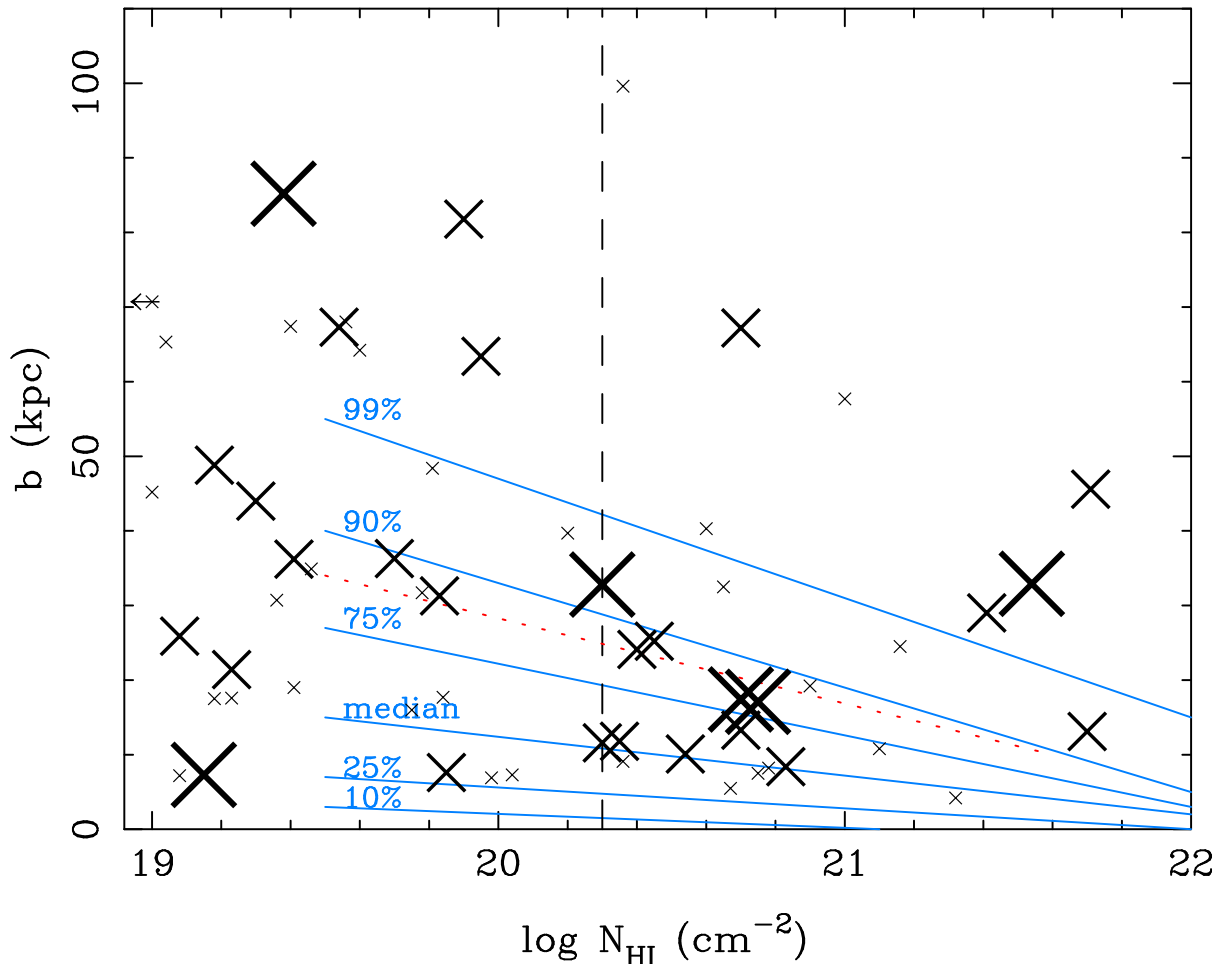


Figure 28. Impact parameter, b , versus $\log N_{\text{HI}}$. The smallest crosses are galaxies in our sample with $L \leq 0.3L^*$, the medium sized crosses are those with $0.3 < L \leq L^*$, and the large crosses represent galaxies with $L > L^*$. The subDLAs and the DLAs are separated by the vertical dashed line. The blue solid lines, adapted from Zwaan et al. (2005), approximate the curves drawn in their Figure 15, which extend only to $\log N_{\text{HI}} = 19.5$. The line labeled “median” indicates that there is a 50% probability that the absorber galaxy will lie below this line. The other lines show the 10th, 25th, 75th, 90th, and 99th percentiles for galaxies at $z = 0$. The red dotted line has been adapted from Figure 18 of Zwaan et al. (2005), and indicates that above this line, more than 50% of the galaxies are more luminous than L^* at $z = 0$.

5 CONCLUSIONS

We have presented the results of an optical/IR imaging programme aimed at studying the properties of $0.1 \lesssim z \lesssim 1$ galaxies giving rise to quasar absorption systems with available neutral hydrogen column densities. Results from 55 quasar fields with 66 absorbers are presented here for the first time. We were able to identify the absorbing galaxy for 54 of these. By combining galaxy identifications from previous studies, we have analysed the properties of a sample of 27 DLA ($N_{\text{HI}} \geq 2 \times 10^{20}$ atoms cm^{-2}), 30 subDLA ($10^{19} < N_{\text{HI}} < 2 \times 10^{20}$ atoms cm^{-2}), and 23 LLS (with N_{HI} not large enough to be DLAs or subDLAs – $3 \times 10^{17} < N_{\text{HI}} \leq 10^{19}$ atoms cm^{-2}) galaxies. All of these absorbers were Mg II -selected. While our sampling of $W_0^{\lambda 2796}$ values is sufficient to include all DLAs, it is unlikely that this holds for subDLAs and LLSs. But we have no *a priori* reason to believe that this significantly affects our results.

Here we summarize the main results from §3 and §4.

1. An analysis of our uniform K -band dataset shows that

the surface density of galaxies falls off exponentially with increasing impact parameter, b , from the quasar sightline relative to a constant background of galaxies, with an e -folding length of ≈ 46 kpc (Figure 6). Galaxies with $b \gtrsim 100$ kpc calculated at the absorption redshift are statistically consistent with being unrelated to the absorption system, and are either background or foreground galaxies. See §3 and conclusion 4 (below).

2. The correlation between the log of the neutral hydrogen column density, $\log N_{\text{HI}}$, and Mg II rest equivalent width, $W_0^{\lambda 2796}$, first reported by RTN06 but subject to the noted caveats, is also present in this imaging sample (§4.4 and Figure 21). Since most of the sample was selected from RTN06, a correlation is expected. The $\log N_{\text{HI}}$ and $W_0^{\lambda 2796}$ parameters are positively correlated at the 4.7σ level of significance (see footnote #8). The median values of $W_0^{\lambda 2796}$ in the imaging sample are 2.0 Å for the DLAs, 1.37 Å for the subDLAs, and 0.78 Å for the LLSs.

3. The galaxy luminosity relative to L^* , L/L^* , is not correlated with $W_0^{\lambda 2796}$, and the b value is only weakly correlated

with $W_0^{\lambda 2796}$ (§4.4). There is an inverse correlation between b and $W_0^{\lambda 2796}$ at only the 1.8σ level of significance (Figure 19). Also, galaxies which give rise to higher $W_0^{\lambda 2796}$ are not significantly systematically more luminous, even if the comparison is made as a function of b (Figure 22).

4. The $\log N_{HI}$ value is inversely correlated with b at the 3.0σ level of significance in the sense that DLA galaxies are found systematically closer to the quasar sightline, by a factor of two, than are galaxies which give rise to subDLAs or LLSs (§4.5 and Figure 24). The median impact parameter is 17.4 kpc for the DLA galaxy sample, 33.3 kpc for the subDLA sample, and 36.4 kpc for the LLS sample. This is not unexpected, since higher column density gas tends to exist at smaller galactic radii, but this is the first time it has been definitively demonstrated among galaxies identified as DLA or subDLA absorbers. We also find that the decline in the median value of $\log N_{HI}$ with b can be roughly described by an exponential with an e -folding length of 12 kpc that occurs at $\log N_{HI} = 20.0$ (Figure 25).

5. $\log N_{HI}$ is not correlated with galaxy luminosity (§4.5 and Figure 26). The median values of luminosity are $0.33L^*$, $0.20L^*$, and $0.31L^*$ for the DLA, subDLA, and LLS samples, respectively. There is also no evidence that, within each sample, galaxies with large impact parameters are more luminous (Figure 26).

6. The b value is not significantly correlated with L/L^* , as a positive correlation is present at only a 1.2σ level of significance (§4.6 and Figure 19).

7. A PCA did not reveal any useful information, i.e., the absorbers do not occupy a preferred direction in the multi-parameter space defined by $W_0^{\lambda 2796}$, $\log N_{HI}$, b , and L/L^* (§4.7).

8. DLA, subDLA, and LLS galaxies comprise a mix of spectral types, but are inferred to be predominantly late type galaxies based on their spectral energy distributions (§4.8).

9. Using measurements of metallicity from the literature, we find no trends between metallicity and b or L/L^* (§4.9 and Figure 27). This is somewhat surprising, but we caution that the samples are small.

10. We find that the properties of low-redshift DLAs and subDLAs are very different in comparison to the properties of gas-rich galaxies at the present epoch (§4.10 and Figure 28). A significantly higher fraction of low-redshift absorbers have large b values, and a significantly higher fraction of the large b value galaxies have luminosities $L < L^*$.

6 DISCUSSION

We have presented results from a Mg II -based quasar absorption line search for galaxies that give rise to DLA, subDLA, and LLS absorption at redshifts $0.1 \lesssim z \lesssim 1$ in the spectra of background quasars. The sample we studied was formed from a larger sample of strong Mg II absorbers ($W_0^{\lambda 2796} \geq 0.3 \text{ \AA}$) whose H I column densities were determined by measuring the Ly α line in HST UV spectra.

Analysis of our data revealed two main correlations. First, by considering the three different N_{HI} column density regimes (i.e., DLAs, subDLAs, and LLSs), we find that $\log N_{HI}$ is positively correlated with $W_0^{\lambda 2796}$ at the 4.7σ significance level (i.e., §5 conclusion 2 and Figure 21). It is

important to realize that because the Mg II absorption lines are generally saturated, $W_0^{\lambda 2796}$ is a proxy for the sightline velocity spread of the absorbing gas associated with the galaxy. Therefore, one can statistically infer that sightlines that intercept larger H I columns of gas generally encounter larger gas velocity spreads. However, this is not a tight correlation. The N_{HI} value cannot be used to predict $W_0^{\lambda 2796}$, nor can $W_0^{\lambda 2796}$ be used to predict N_{HI} . One interpretation is that the gas that is primarily responsible for a DLA is one of many clouds along the line of sight. The larger the Mg II rest equivalent width, the more clouds along the sightline, and the higher the probability of one of them being the cloud that produces a DLA. This explains why, for example, a strong Mg II system is not always a DLA, and why weaker Mg II systems can occasionally be DLAs. The threshold $W_0^{\lambda 2796} = 0.6 \text{ \AA}$, below which no DLAs are found, is then representative of the minimum velocity spread of a region containing DLA clouds.

Second, we found that the median impact parameter of a sample of DLA galaxies is approximately half that found for samples of subDLA and LLS galaxies (i.e., §5 conclusion 4 and Figure 24). SubDLA and LLS galaxies have similar impact parameter distributions. This second correlation has a 3.0σ level of significance. Again, this is not a tight correlation. To emphasize this, we note that three of our DLA galaxy identifications have impact parameters $b > 50$ kpc, while six of our subDLA and LLS galaxy identifications have $b \leq 10$ kpc. It does, however, seem unreasonable to expect a tight correlation for either of these two main correlations. This is because the observed impact parameter is set by the chance separation between the absorbing galaxy and the quasar sightline. That is, the observed impact parameter for an absorbing galaxy only indicates that the radial extent of the gas surrounding the galaxy extends at least as far out as the impact parameter (see discussion of equation 1, below). The median impact parameter for DLA galaxies is ≈ 17 kpc, whereas it is ≈ 35 kpc for subDLA and LLS galaxies. But there is wide overlap in the distributions of impact parameters among the three identified galaxy samples, as expected. In combination these two findings suggest that systems with lower b values should generally have larger $W_0^{\lambda 2796}$ values and vice versa, and indeed a weak inverse correlation at a 1.8σ level of significance is seen (i.e., §5 conclusion 3 and Figure 19).

Taken together, the observed trends, although weak, indicate that DLAs generally have higher values of Mg II $W_0^{\lambda 2796}$, smaller impact parameters, lower metallicities, and similar luminosities in comparison to subDLAs. That subDLA and DLA galaxies have similar luminosities implies that the subDLAs are not more massive, which was a suggestion made by Kulkarni et al. (2010) to explain their higher metallicities. The mass-metallicity relation does not appear to play a role here. That DLA sightlines have higher velocity spreads but lower impact parameters is an indication that the gas is not rotationally supported. As suggested by several studies, superwinds and tidal gas from mergers are likely to be involved (see below).

The absence of tight correlations may also be due to the patchiness of H I absorbing gas and misidentifications of “true” absorbing galaxies. For example, with regard to the H I gas being patchy, Monier et al. (2009b) found that N_{HI} changed from the DLA to the subDLA regime over sightline

changes as small as ≈ 5 kpc at $z \approx 1.5$. Cooke et al. (2010) studied a $z \approx 1.63$ DLA with $N_{\text{HI}} \approx 5 \times 10^{20}$ atoms cm^{-2} , but along an adjacent sightline separated by 2.7 kpc found that the H I column density dropped to $N_{\text{HI}} < 1.3 \times 10^{18}$ atoms cm^{-2} . This suggests that a slight change in sightline separation, which is much smaller than the observed b value, influences classification of the absorbing galaxy as a DLA, subDLA, or LLS galaxy. This would clearly increase the intrinsic spread in correlations with N_{HI} . Since we did not form a control sample of galaxies that *do not* give rise to absorption lines in the spectra of background quasars, our current work offers no conclusions on the covering factor of $W_0^{\lambda 2796} \geq 0.3$ Å Mg II absorbers. However, we note that with their absorbing and non-absorbing galaxy samples, Kacprzak et al. (2008) obtain a mean covering factor of $\approx 50\%$ for $W_0^{\lambda 2796} \geq 0.3$ Å Mg II gas. Chen et al. (2010) derive a covering factor of $\approx 70\%$ for $W_0^{\lambda 2796} \geq 0.3$ Å absorbers and $\approx 80\%$ for $W_0^{\lambda 2796} \geq 1.0$ Å absorbers. Even though information on H I column density is unavailable in these other analyses, these results also provide evidence for patchiness which would increase the intrinsic spread in correlations.

With regard to the possible misidentification of absorbing galaxies, consider our identifications for two DLA absorbing galaxies (§3) with impact parameters of $b \approx 67$ kpc (for a $0.7L^*$ galaxy) and $b \approx 100$ kpc (for a $0.05L^*$ galaxy). These may both be outliers, but certainly the identification of the second one seems far-fetched. However, there is another possibility which may put such identifications in context. Recently, Kacprzak et al. (2010) published cosmological simulations to aide in the interpretation of their observations of Mg II -absorption-selected galaxies at intermediate redshift. Their simulations indicate that, relative to a central galaxy, Mg II absorption selects metal-enriched halo gas, tidal streams, filaments, and small satellite galaxies. In particular, they find that H I column densities in the DLA regime can arise in low-mass satellite galaxies at impact parameters as large at ≈ 100 kpc. Our large impact parameter DLA galaxies may be examples of such cases, and in that sense they may be misidentifications since the small satellite galaxies would not be identified because of the glare of the background quasar. It is therefore useful to use our results to consider the overall radial gaseous extent of our identified absorbing galaxies as a function of galaxy of luminosity L , i.e., $R(L)$. However, it seems appropriate to interpret results on $R(L)$ in the context of the Kacprzak et al. (2010) simulations in which “halo” gas can have a variety of origins, including the possibility that the observed absorption arises in a neutral-gas-rich satellite galaxy which resides in the environment of the galaxy we identify as the absorbing galaxy.

Another result worth mentioning is the $z_{\text{abs}} = 0.006$, $\log N_{\text{HI}} = 19.3$, subDLA system towards PG 1216+019 (Tripp et al. 2005), which is an example of an absorbing galaxy that was detected in H I emission alone. Briggs & Barnes (2006) report on the detection of a 21 cm line emitter that has M_{HI} between 5 and $15 \times 10^6 M_\odot$, and is within ~ 4 kpc of the quasar sightline. No optical counterpart to this H I emitter has been detected thus far (Chen et al. 2001, Tripp et al. 2005), implying that any optical emission from this galaxy might be hidden under the glare of either the quasar PSF or that of a nearby ($10''$ away) star.

Other H I emitting objects within 100 km s^{-1} of the absorption redshift are a $0.25L^*$ galaxy at a distance of 92 kpc from the quasar sightline and an optically-undetected, $M_{\text{HI}} \sim 3 \times 10^8 M_\odot$, object 120 kpc from the quasar sightline. This suggests that the absorber is likely to be tidal debris or diffuse gas in the halo of one or both of the two more massive galaxies (Briggs & Barnes 2006). Thus, here is a case where the $b = 92$ kpc galaxy would have been identified as the absorber in the absence of the 21 cm data, when in fact, a much smaller b , low-mass dwarf galaxy is the true site of absorption.

Past attempts have been made to derive a radius-luminosity scaling relationship for absorbers in order to infer the extent of gaseous halos (e.g., Steidel 1995, Guillemin & Bergeron 1997, Kacprzak et al. 2008, Chen et al. 2010). The scaling relation is a power law of the form

$$R(L) = R_*(L/L^*)^\beta, \quad (1)$$

where R denotes the radial gaseous extent of a galaxy of luminosity L . For our data this is illustrated by the upper envelope of a plot of b versus L/L^* . In the left panel of Figure 29 we plot b versus $\log L/L^*$ for galaxies in our sample with K -band data. In the right panel we plot this for our entire sample using a compilation of measurements in several wavebands (see Tables 14 and 15). We show the K -band data separately because measurements in the literature generally use a single waveband, however a comparison between the left and right panels shows that the two distributions of data points are similar, and that the conclusions do not change when we include our entire sample. The two solid curves in the two panels are power laws of the form shown in Equation 1, and encompass the range of possible upper envelopes to the data points. The shallower power law has $R_* = 89$ kpc and $\beta = 0.08$, and the steeper power law has $R_* = 120$ kpc and $\beta = 0.29$. Both power laws do not include the outlier at $b \approx 100$ kpc and $L \approx 0.05L^*$. This is the galaxy that is identified as the $z_{\text{abs}} = 0.656$ DLA absorber towards 1622+239 (Kacprzak et al. 2007). It is also inconsistent with the other models from the literature, and is therefore, almost certainly a misidentification. The two data points at $b \approx 65$ kpc and $\log L/L^* \approx -1.3$ are identifications with confidence levels $\text{CL} = 2$, where the identifications were not straightforward. It could well be that these galaxies were misidentified. On the other hand, of the two LLSs with impact parameters $b > 90$ kpc, one is a spectroscopic identification, while the other has $\text{CL} = 3$. Therefore, the steeper power law, i.e., the solid curve with $\beta = 0.29$, may be a more adequate representation of the upper envelope of gaseous halos of strong Mg II absorbers, although the shallower power law cannot be ruled out because of the small number of galaxies that define the upper envelope. In any case, these data indicate that the characteristic size of the gaseous halo (environment) of an L^* galaxy is likely to be as large as 120 kpc, larger than any of the previously derived values.

The K08 (Kacprzak et al. 2008) and C10 (Chen et al. 2010) models shown in Figure 29 are roughly consistent with the data, although the C10 model excludes more data points. The S95 (Steidel et al. 1995) and GB97 (Guillemin and Bergeron 1997) models are clearly ruled out by our data.

It is now clear from the more recent studies that gas extends much farther out from the centers of galaxies than previously thought. For example, the conclusion from ini-

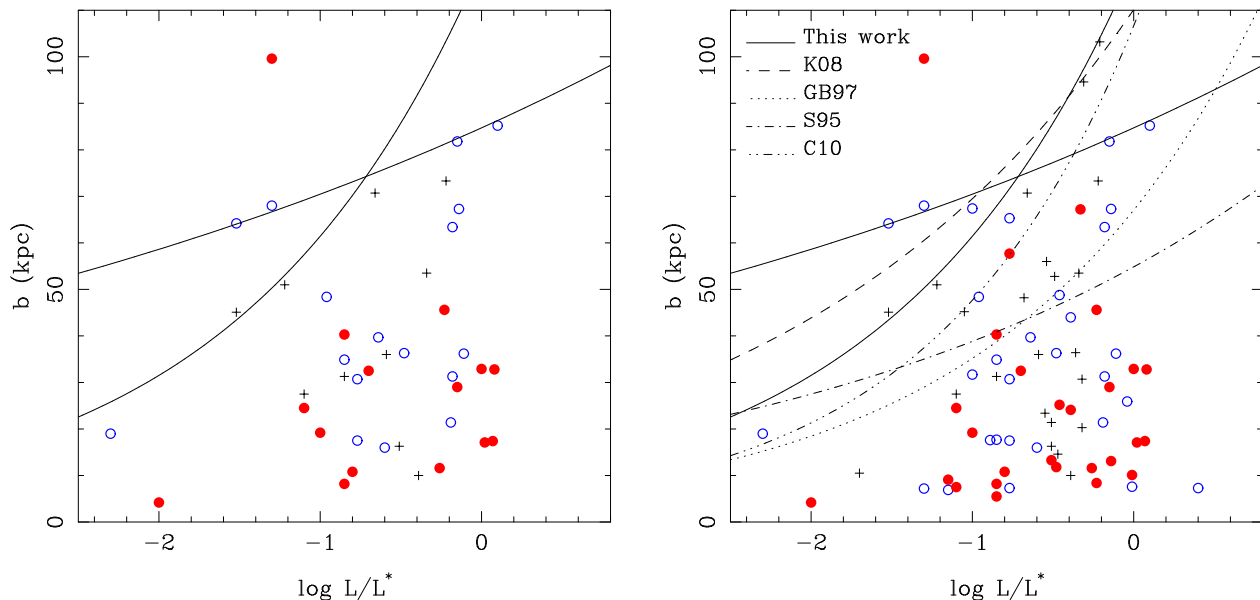


Figure 29. Impact parameter, b , versus luminosity, $\log L/L^*$, for K -band data (left panel), and for the entire sample (right panel). Red solid circles are DLAs, blue open circles are subDLAs, and plus symbols are LLSs. The solid lines are the same in both panels: they are power laws of the form $b = 89(L/L^*)^{0.08}$ kpc (the shallower one) and $b = 120(L/L^*)^{0.29}$ kpc, and are drawn to encompass the range of possible upper envelopes to the data. The other power laws are from previously published work: K08: Kacprzak et al. (2008), GB97: Guillemin & Bergeron (1997), S95: Steidel (1995), and C10: Chen et al. (2010). See text.

tial studies that there is always a bright, L^* , galaxy associated with strong Mg II absorbers, and that the galaxies have gaseous disks that are ~ 40 kpc in radius, is no longer supported. Only nine out of 80 galaxies in our sample are $\sim L^*$ or brighter. It is also clear that the gas distribution within galaxies is patchy, much like what is seen in high resolution 21 cm maps of local galaxies (e.g., Zwaan et al. 2005; Braun et al. 2009). However, at larger galactocentric distances processes such as star-formation induced outflows (Weiner et al. 2009), radiatively driven winds (Murray et al. 2010), infalling gas in filaments, tidal streams and satellite galaxies (Kacprzak et al. 2010), and superwinds and tidal gas from mergers and interactions (Zwaan et al. 2008) appear to be playing an important role. Illustration of our results at $z \approx 0.1 - 1.0$ in Figure 28 apparently demonstrates the importance of some of these processes at low-to-moderate redshift. In Figure 28 we show our results in conjunction with local ($z \approx 0$) results on H I gas in galaxies adapted from Zwaan et al. (2005). Our results at low-to-moderate redshift are inconsistent with the $z \approx 0$ results, suggesting that we are detecting evolution in the neutral-gas environments of galaxies.

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APPENDIX A: PHOTOMETRIC REDSHIFT DETERMINATIONS

Photometric redshifts are determined using the template fitting method through a χ^2 minimization procedure. Conti

et al. (2003) describe the details of this procedure, and we summarize it here. This approach compares the expected colours of a galaxy derived from template spectral energy distributions (SEDs) with those observed for an individual galaxy. Each SED template is redshifted, convolved with the photometric filter response curves, and compared with the observed fluxes through each filter. A redshift dependent $\chi^2(z)$ is defined as

$$\chi^2(z, T) = \sum_{i=1}^{N_{filters}} \left[\frac{F_{obs,i} - b_j \times F_{i,j}(z, T)}{\sigma_i} \right]^2 \quad (A1)$$

where $F_{obs,i}$ is the flux of the galaxy observed through the i th filter, $F_{i,j}$ is the flux of the j th template observed through the i th filter at redshift z , σ_i is the error in the observed flux in the i th filter, and b_j is a normalization constant. The sum is carried out over all available filters, $N_{filters}$. The resulting χ^2 is minimized as a function of z and template, T , giving an estimate of the galaxy redshift with its variance and spectral type parameters. This algorithm is courtesy of T. Budavári (2003, private communication).

Conti et al. (2003) used the Bruzual & Charlot (2003) population synthesis models to generate SED templates that are used to fit the photometry of the detected galaxies. Each SED template is the result of modeling the detailed physical processes affecting star formation efficiency and gas properties. These SEDs are used for the current analysis. The parameters selected to generate the templates are chosen to sample a wide range of physical characteristics, i.e., age, star formation rate (SFR), obscuration, and metallicity. A Salpeter initial mass function (IMF) with low- and high-mass cutoffs equal to $0.1 M_{\odot}$ and $125.0 M_{\odot}$ is assumed for all of the SEDs. The stellar populations sample 10 ages, ranging from extremely young (0.001, 0.01, 0.1, 0.5 Gyr), middle (1.0, 3.0, 5.0 Gyr) to old (9.0, 12.0, 15.0 Gyr). An exponential SFR with an e -folding time τ of the form, $\Psi(t) = \Psi_0 e^{-t/\tau}$ is applied. This form describes an instantaneous burst when $\tau \rightarrow 0$ and a constant rate of star formation when $\tau \rightarrow \infty$. The e -folding times used in generating the SEDs are $\tau = 0.1, 1.0, 3.0, 5.0, 9.0$, and 12.0 . The metallicity is allowed to be $\frac{1}{200}$ to 2.5 times solar: $Z = 0.0001, 0.0004, 0.004, 0.008, 0.02, 0.05$, where Z is the metal mass fraction with $Z_{\odot} = 0.02$. A Calzetti et al. (2000) extinction law of the form $k(\lambda) = A(\lambda)/E_{B-V}$ is applied where the following values of magnitudes of extinction are allowed: 0.0, 0.1, 0.2, 0.3, 0.5, 0.9. This results in a total of 2160 templates (Conti et al. 2003).

Photometric redshifts are calculated for objects detected in fields for which data in four or more filters are available. SDSS optical photometry, when available, is used to supplement our photometry of fields for which we have only infrared data. The photometric redshift, z_{phot} , is deemed consistent with the absorption redshift, z_{abs} , when z_{abs} is included in the range spanned by the 1σ z_{phot} errors.